A Taxonomy of Human Grasping Behavior Suitable for Transfer to Robotic Hands

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***Abstract*— As a first step towards transferring human grasping capabilities to robots, we analyzed the grasping behavior of human subjects. We derived a taxonomy in order to adequately represent the observed strategies. During the analysis of the recorded data, this classification scheme helped us to obtain a better understanding of human grasping behavior. We will provide support for our hypothesis that humans exploit compliant contact between the hand and the environment to compensate for uncertainty. We will also show a realization of the resulting grasping strategies on a real robot. It is our belief that the detailed analysis of human grasping behavior will ultimately lead to significant increases in robot manipulation and dexterity.**

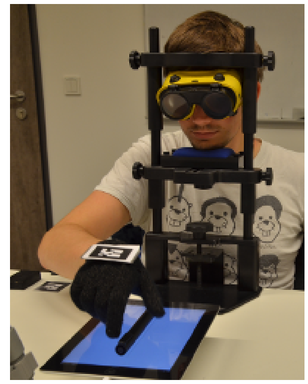

Fig. 1. We develop a taxonomy of human grasping behavior based on five subjects grasping ten objects in the illustrated experimental setup. We record hand position, timed contact point traces on the support surface, contact force, and three different video streams. Grasping was performed with normal vision and with vision impaired by goggles with frosted glass.

I. Introduction

Human grasping performance is far superior to that of robots. This is in part due to the purposeful exploitation of contact in human grasping: humans routinely leverage contact with the environment to achieve robustness in the presence of uncertainty [1], [2]. Human grasping thus stands in contrast to the traditional robotic grasping literature, in which contact with the environment—other than with the grasped object itself—is to be avoided. If, however, this difference can indeed explain some of the discrepancy in performance, it is only natural to replicate human grasping strategies on robots. A first step towards this goal must be a characterization and analysis of human grasping behavior. This characterization should pay particular attention to the use of contact, i.e., the *exploitation of contact constraints* to compensate for uncertainty in perception or control.

We derive a taxonomy of human grasping behavior by analyzing 500 grasping trials with five subjects and ten objects in two different conditions [1]. This taxonomy *(a)* characterizes constraint exploitation strategies employed by humans, *(b)* only contains sub-behaviors that can be replicated as visually-servoed or guarded moves on a robot, and *(c)* explains all of the grasping behaviors observed in our trials. We provide preliminary evidence that the resulting taxonomy can serve as a basis for generating human-inspired, constraint-exploiting robotic grasping behavior.

The proposed taxonomy does not capture the diversity of human dexterous manipulation behavior in its entirety. We analyzed human grasping of a limited set of objects placed on a clutter-free, flat surface. However, our analysis and the resulting taxonomy provide first support for the hypothesis that routine human grasping behavior can be explained with a relatively small set of sequenced and robot-replicatable sub-behaviors. This result is encouraging, as it indicates that human capabilities might possibly be transferred to robots one day by employing the principle of constraint exploitation.

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II. Related Work

Of the many taxonomies of human grasping behavior, the earliest classifications distinguish hand posture in power and precision grasps [3]. Posture varies with object size, shape, and task requirement (intended activity). Similar observations were made in studies with primates [4], [5], [6].

In robotics, one of the earliest taxonomies of grasping postures was developed by Cutkosky [7]. It was used to label human grasps for a variety of everyday tasks [8]. Together with over 30 other taxonomies, it was combined into a single one [9]. All of these taxonomies analyze static hand postures as a function of object and task properties. They do not, however, capture the pre-grasp interactions that finally lead to those postures, probably because they were not deemed important. In the context of this paper, however, they will play a central role.

In psychology and neuroscience, human grasping behavior is analyzed based on the spatio-temporal evolution of the grasping motion [10]. Here, the central point of studies are two coordinated and collaborative motor components: hand transportation and finger grip. Parameters describing those components include maximum grip aperture (MGA), movement time, and time to peak acceleration / velocity / deceleration. Other studies differentiate between different phases of the grasp, such as reach, load, lift, hold, replace, and unload [11]. These parameters are relevant to characterizing human grasping and manipulation skills but do not capture the characteristics of motion relevant for the transfer of human exploitation of environmental constraints to robots.

In the present work, we are particularly interested in actions of the hand that prepare for the final grasp posture, i.e., constraint-exploiting motions contributing to robustness in performance. In-hand manipulation can be viewed as a sequence of such preparatory motions. Taxonomies of human in-hand manipulation distinguish between finger-to-palm translation, palm-to-finger translation, shift, simple rotation, and complex rotation [12], [13]. Another pre-grasp interaction taxonomy for object adjustments distinguishes rigid/non-rigid reconfigurations, and among those: rotation, displacement, tumbling, etc. [14]. All of these taxonomies characterize human in-hand manipulation but are not concerned with transferring those skills to a robotic hand.

In the next sections, we will propose a taxonomy that evolved from the analysis of human grasping behavior. Its purpose is the transfer of human grasping capabilities onto robotic hands. Such transfer has been realized before in the robotics literature: the transfer of grasping strategies for particular object geometries [15], the transfer of multi-step strategies where transitions between the individual steps are triggered by sensory events [16], the transfer of postural synergies [17], [18], and the transfer of human-demonstrated grasps to novel objects [19]. In this work, we hope to lay the initial foundation for a general and principled way of performing such transfers.

III. Data Collection

To gather the data that provide the basis for our taxonomy of human grasping behavior, we performed an experiment explained in detail in [1]. In this section, we shortly introduce the experimental procedures and data analyses.

Five right-handed subjects (aged 20–25 years, two females) participated in the experiment. They had no prior knowledge of the purpose of the experiment. Figs. 1 and 2 depict the experimental setup and the positioning of the graspers relative to the objects.

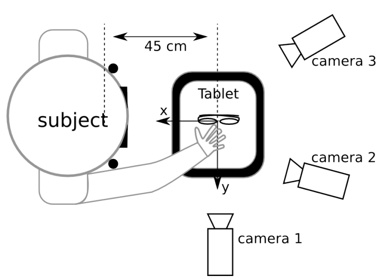

Fig. 2. Experimental setup of the grasping experiment: schematic diagram.

Observers grasped ten different objects (see Fig. 3, left panel) which were presented in a randomized sequence to each observer. Objects were placed in a fixed position and orientation on a touch screen device. The device was mounted on top of a force/torque sensor. In order to prevent observers from seeing the placing of objects, their view of the scene was obstructed with a cardboard. The start of each trial was indicated by a tone and the cardboard was removed. Then the observers lifted their hand in order to reach for the object. The trial finished with the lift of the object. The hand of the observer was tracked with three cameras and a Quick Response (QR) marker on the back of the right hand. The finger positions on the surface were recorded with a touch screen device and conductive gloves. One trial lasted between one and five seconds. To manipulate sensory uncertainty about the objects, we impaired the subject's vision with frosted-glass goggles. Fig. 3 illustrates the appearance of the objects in the impaired condition and in the regular viewing condition. In total, observers grasped every object five times in the two viewing conditions which amounted to a total of 100 trials per participant.

Fig. 3. The images show the objects used in our experiments in the control condition (left) and the impaired condition (right).

The collected data contained the hand posture (in x-y-z coordinates), the duration of the grasp, the finger positions on the touch pad as a function of time, the number of contacts, the aggregated contact force resulting from all contact with the surface, and the video data obtained from three different vantage points (see Fig. 2).

IV. Taxonomy

A. *Why We Need a Taxonomy*

To enable transfer of human grasping strategies onto robots, we need an adequate representation of the behavior observed in the experiments. This representation must enable grouping behaviors such that each group corresponds to a type of behavior replicatable on a robot with a distinctive motion primitive. Other authors have proposed a candidate representation [2], namely heat maps. These are graphical depictions of the frequency of occurrence of finger contacts at a certain position on a support surface. However, we observed that analyzing the contacts with the support surface alone does not suffice to distinguish different grasp strategies. To show this we compared the finger traces on the touch pad for different objects. We found that those may result in similarly looking traces although different grasp strategies were used. An example for this is shown in Fig. 4. Here, a strategy that we labelled ’flip’ (see below) produced traces that are almost identical to the ones produced by a different one (’closing’). That the two strategies indeed capture different grasping behaviors is illustrated in the snapshots from the respective video recordings that are depicted below the contact traces. We conclude that contact traces, or their aggregated variant, i.e., heat maps, are insufficient to characterize human grasping and potential interactions with the environment. That’s why we created the taxonomy based on observations through the experiment and inspection of the recorded video data.

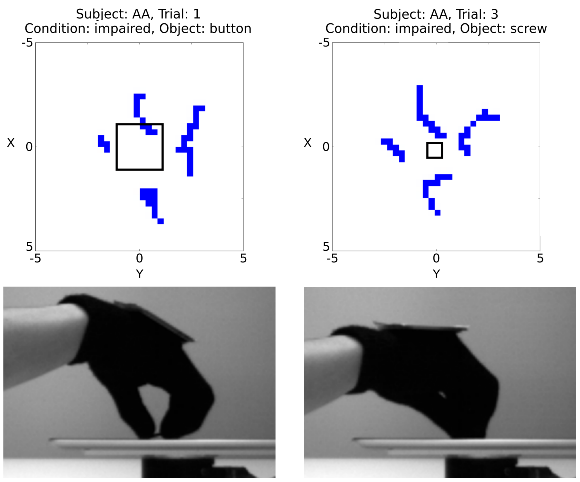

Fig. 4. Two different grasp primitives together with their respective contact traces. Left: The primitive ’flip’ (the fingertips are brought under the object while it is being stabilized by the thumb). Right: The primitive ’closing’ from the ’top’ that is ’constrained’ and leads to ’no rotation’ of the object. (the fingertips are just being brought together)

B. Description of the taxonomy

The basic components in our taxonomy are *grasp primitives*. A grasp primitive consists of an action which represents the main hand movement and of several modifiers that provide additional information for the action. A *grasp strategy* may consist of several grasp primitives in succession and it ends when the object is lifted off the support surface.

We identified six types of primitives in the recorded data. This set is necessary and sufficient to describe the observed grasping behavior: reach, close, slide, edge-grasp, flip and fail (Fig. 5). We will describe each of these in turn.

1) The action ’reach’ refers to the approach of the hand towards the object. It starts when the hand leaves the resting state and it ends when the hand has contact with or closes around the object. The action ’reach’ has the modifiers ’side/top’ which indicate the orientation of the hand during approaching and ’constrained/unconstrained’ which indicate whether the hand had contact with the support surface. It should be noted that in a few number of cases it was hard to differentiate between constrained and unconstrained reaches, because the touch pad did not recognize a ground contact that was evident in the video.

2) The action ’closing’ describes the motion of the hand and the fingers that leads to a force closure grasp. We noticed that the actual closing motion of the hand was almost identical for most of the objects, whereas the final position of the fingers was a result of the shape of the object and the compliance of the hand. Further experiments with a greater number of objects would be required in order to test whether the closing motion is indeed highly stereotypical or whether a greater variety of objects would result in a greater variety of closing motions. The ’closing’ action has the modifiers ’side/top’ and ’constrained/unconstrained’ which often occurred as a continuation of the previous reach. In addition, it has the modifier ’rotation/no rotation’ which indicates whether the object rotated while the hand was being closed.

3) The action ’slide’ causes object motion while the object is still in contact with the surface, i.e., without lifting it.

4) The ’edge grasp’ action is a form of hand closing after the object was moved over the edge of the support surface. This action effectively changes the object geometry accessible to the hand by exposing the bottom side of the object.

5) The action ’flip’ describes the motion of bringing the fingertips under the object while using the thumb to fix part of the object to the surface. This primitive also changes the object geometry accessible to the hand.

6) Finally the action ’fail’ indicates that a grasp strategy failed. Failures were always followed by a new initiation of one of the actions described above.

In Fig. 5, the taxonomy is depicted as a tree, in which every leaf represents one fully instanced grasp primitive. The tree structure has been chosen for illustrative purposes and the hierarchy of the different types of modifiers was assigned arbitrarily. The individual characteristics of the actions determined the associated modifiers. Some actions, like ’reach’ and ’closing,’ share some of the same modifiers while other actions, like ’flip’, have no modifier. It should be noted that the taxonomy represents an abstraction of the observed behavior. Hence, despite its proven practical applicability (see Section VI), it is sometimes difficult to determine when one grasp primitive ends and another one starts, as they might overlap each other. Nevertheless, our evaluation will demonstrate the useful properties of the proposed taxonomy.

V. Evaluation of the Taxonomy

We will argue that the proposed taxonomy provides a necessary and sufficient basis for the representation of the observed grasping behavior. The classification of the behavior was performed by human labelers who analyzed the data and assigned grasping primitives to it. We will evaluate its adequacy on the basis of two standard criteria for the critical evaluation of the quality of psychometrical tests: The *reliability* of a test is the overall consistency of the measure, whereas the *validity* is the extent to which it actually measures the concept it is supposed to measure.

A. Reliability

We addressed the consistency of the taxonomy by assessing the degree of agreement between two labelers who

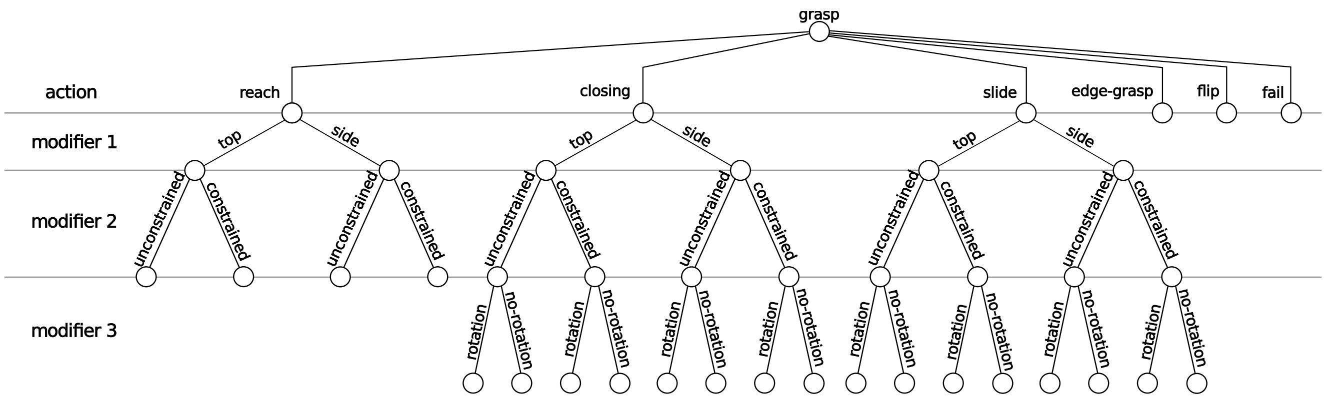

Fig. 5. The actions and modifiers of the taxonomy: every path from the root to a leaf corresponds to a grasp primitive

independently labelled the behavior observed in the videos according to the categories in the taxonomy. To quantify the similarity between the two different labelings, we computed the Levenshtein distance. It defines the difference between two strings as the minimum number of operations (i.e., insertions, deletions, or substitutions) needed to transform one string into the other. We therefore represented the recorded grasp strategies as sequences of actions with their respective modifiers (the order of the modifiers was fixed). Consider the labelings L_1 and L_2 for example:

$$L_1 = [\text{reach}, \text{top}, \text{unguided}, \text{closing}, \text{top}, \text{guided}, \text{no rotation}]$$
$$L_2 = [\text{reach}, \text{top}, \text{guided}, \text{closing}, \text{top}, \text{guided}, \text{rotation}, \text{flip}]$$

The Levenshtein distance for transforming L_1 into L_2 is three, as in L_1 the modifiers 'unguided' and 'no rotation' need to be substituted by 'guided' and 'rotation' and the action 'flip' needs to be appended.

Fig. 6 shows that in over 74% of the trials, the labeling between the two labelers was identical. In the remaining cases, for the majority of trials we obtained a Levenshtein distance of 1 and this resulted most often from a difference in labeling with respect to a modifier. These data indicate a high degree of consistency in the mapping between labels and grasp primitives for the two independent labelers and the tested objects, indicating a satisfactory degree of reliability for the proposed taxonomy.

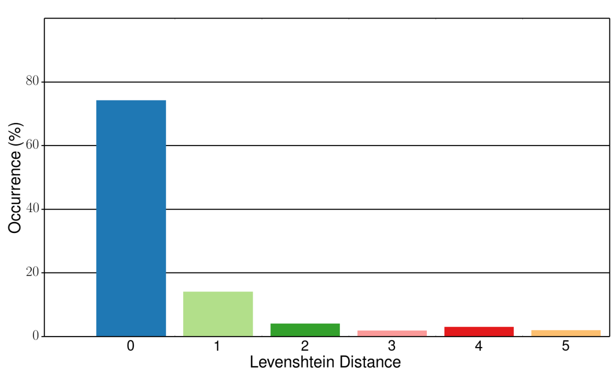

Fig. 6. Occurrence of Levenshtein distance for the two labelings

B. Validity

In order to validate the taxonomy, we considered the following aspects related to the concepts of content and criterion validity. The content validity concerns the question whether a test covers all relevant aspect of the behavioral domain that it aims to address. With the present taxonomy all observed behavior could be assigned to one of the grasp primitives (one of the leaves in Fig. 5). No residual category was required. On the other hand, all labels were assigned at least once, which shows that no unnecessary labels were chosen. A question that needs to be addressed in future experiments is whether some grasp primitives would be observed more frequently when a different set of objects is used, and whether this might also require a higher degree of differentiation of the taxonomy.

Criterion validity refers to the performance of a test in comparison to other tests for which validity has already been established. Here we want to compare the taxonomy-based results with those from earlier studies with respect to the hypothesis that humans rely more heavily on environmental constraints when grasping is performed under impaired visual conditions.

It has previously been shown that introducing uncertainty by means of impaired vision resulted in a greater spatial spread of the finger contacts ([2]). We also observed that difference in our data (Fig. 7).

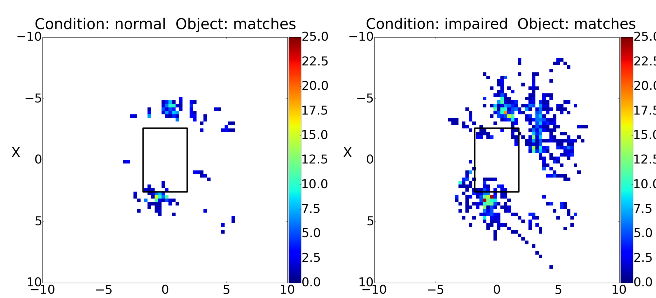

Fig. 7. Spread of finger contacts for normal and impaired condition for all subjects for the object 'matches': the impaired condition leads to greater spatial spread of the finger contacts

Crucially for the question concerning the criterion validity of the taxonomy, this effect is also evident in measures derived from the taxonomy. Of all the failed primitives, a total of 76% occurred in the impaired vision condition, justifying the conclusion that impaired vision made grasping more difficult. In addition, an analysis of the grasping actions in terms of the taxonomy revealed that different levels of uncertainty lead to different grasp strategies for the same object. We will use the 'reach' and 'closing' actions to illustrate the relation between sensory uncertainty and the use of environmental constraints.

Tab. I shows that most of the reaching was done without surface contact. However, of the 11% of the trials that did involve surface contact, almost all of them were performed in the impaired vision condition. In contrast, trials performed with unconstrained reaching were distributed more or less evenly between the normal and impaired vision conditions.

TABLE I

CONSTRAINED / UNCONSTRAINED REACHING AND CLOSING. PERCENTAGE OF OCCURANCE OF THE SPECIFIC GRASP ACTION. THE ABSOLUTE NUMBER OF OCCURENCES IS GIVEN IN PARENTHESIS.

	constrained	unconstrained
reaching	11% (107)	89% (879)
normal vision	8% (9)	54% (475)
impaired vision	92% (98)	46% (404)
closing	79% (756)	21% (207)
normal vision	43% (322)	71% (146)
impaired vision	57% (434)	29% (61)

In contrast to reaching, closing involved surface contact in most of the trials (see Tab. I). The closing primitive thus seemed to benefit significantly from an interaction with the environment. But in spite of this difference to the reaching primitive, we observed the same general phenomenon: constrained closing occurred more often with impaired vision whereas unconstrained closing occurred more often with normal vision.

TABLE II

ROTATION AND SLIDE IN THE NORMAL AND IN THE IMPAIRED CONDITION.

	normal vision	impaired vision
rotation	38% (74)	62% (122)
slide	39% (29)	61% (46)

The labelled data revealed that the introduction of uncertainty also influenced the occurrence frequencies of action modifiers. When vision was impaired, object rotation was observed more frequently (Tab. II). This can be attributed to the following strategy: with normal vision observers adapted their hand position relative to the object's orientation prior to contact with the object. In the impaired vision condition observers maintained a fixed hand orientation and then compliantly rotated the object upon contact in order to accomplish a more stable grasp. The same reasoning can be applied to the slide action. Because of the higher visual uncertainty in the impaired vision condition, observers were more likely to perform tactile manipulation of the objects so as to transfer them into a better grasping position.

The above mentioned facts support our hypothesis: when humans grasp under impaired visual conditions they use environmental constraints to overcome sensory uncertainties. Our ability to make meaningful statements about the nature of human constraint exploitation based on our taxonomy attests to the taxonomy's validity.

C. *Suitability for Transfer to a Robot*

The ultimate proof of transferability will be a complete transfer which is desired for future work. However, in Section VI, we will show an example of such a transfer. Here, we would like to argue that, in principle, all of the grasping primitives can be realized by well-established techniques in robotics. All five types of primitives represent actions previously realized on a variety of robotic platforms. The modifiers 'side/top' represent different relative poses of the hand relative to the supporting surface. The modifiers 'constrained/unconstrained' capture position- and position/force-controlled motion, respectively. And the modifiers 'rotation/no rotation' capture motion of the object relative to the support surface caused by the robotic hand. It is therefore conceivable that all of the strategies can be implemented on a robotic systems.

D. *Objectivity Versus Dependence On the Set of Objects*

It is intuitively appealing that the grasp strategy depends on the shape of the object. This poses a problem to any kind of experiment that attempts to understand general mechanisms of grasping, because the observed strategies might be specific to the selected set of objects. We think that classifying grasping actions within the taxonomy allows a systematic characterization of how object shape influences different grasp primitives. Below we will show a number of examples that illustrate the differential employment of actions and modifiers when different objects are being grasped.

Not surprisingly, we found that some objects were more difficult to grasp than others. In our set of objects, the *button* and the *comb* resulted in a higher number of 'fails' (88%) than the other eight objects. A related observation is that 100% of the 'flips', 97% of the 'edge-grasps' and 88% of the 'slides' were used to grasp the *button* or the *comb*. The comb and the button differed from the other objects in their comparatively small height. This indicates that the 'slide', the 'flip,' and the 'edge-grasp' seem to be grasp strategies that are particularly well-suited for grasping flat objects.

Tall objects on the other hand were more likely to be grasped from the side. Whereas most objects were grasped from the top, in 89% of the trials in which subjects grasped from the side, they were grasping the *toy* or the *salt shaker*, the two tallest objects in the set. We made similar observations for the 'rotation/no-rotation' modifier when subjects were grasping the *glasses*, the *comb*, or the *marker*. 98% of the rotations were performed with these three objects.

These objects were the most elongated ones in the set and they were placed in an orientation orthogonal to that of the observer. The natural way to grasp these objects is to rotate the object until its axis is aligned with the grasping axis of the hand. This action was sometimes performed passively as a consequence of closing the fingers.

The above observations suggest that we need to understand which object properties are more likely to result in grasp failures or in particular grasp actions. This would allow us to predict when to apply each strategy so that the transfer to robotic grasping will be successfull for different objects.

VI. Transfer To Robotic Grasping

Successful transfer of the proposed taxonomy to a robotic platform is shown by an exemplary grasping skill on a robot. We used a 7-DoF Barrett WAM with an attached F/T sensor and a 4-DoF Barrett hand BH-262. In Fig. 8, the constrained closing from top with rotation of the marker from the human experiment is shown. The grasping controller lowers the hand towards the table surface until a force threshold is reached. It then closes the fingers while compliantly pushing the wrist against the table to maintain fingertip contact [2]. The unconstrained version of this grasp failed consistently due to the small size of the marker relative to the hand [1]. This provides preliminary evidence that the exploitation of environmental constraints can significantly contribute to grasp success and robustness, as it did in our human grasping experiments. Based on the proposed taxonomy we plan to transfer more grasp primitives to the grasping repertoire of the robot.

Fig. 8. Transfer to a robot: constrained closing from top with rotation

VII. Conclusions

We analyzed the grasping behavior of human subjects, in particular with respect to their use of contact constraints to compensate for uncertainty, pursuing the aim of transferring the observed strategies to robotic graspers. We proposed a taxonomy and showed its reliability and validity, two important criteria for the evaluation of psychometric tests. The taxonomy *(a)* characterizes constraint exploitation strategies employed by humans, *(b)* only contains sub-behaviors that can be replicated as visually-servoed or guarded moves on a robot, and *(c)* explains all of the grasping behaviors observed in our trials. We analyzed the corresponding labeling of the recorded data and obtained useful insights into human grasping behavior. One important insight is the importance of exploiting contact constraints to achieve grasp robustness. We showed that transferring this insights to robotic grasping improves grasping performance. We believe that the careful analysis of human grasping strategies and the transfer of resulting insights to robotic graspers is a helpful approach towards dexterous robots.

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