# Exploitation of Environmental Constraints in Human and Robotic Grasping

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**Abstract** We investigate the premise that robust grasping performance is enabled by exploiting constraints present in the environment. These constraints, leveraged through motion in contact, counteract uncertainty in state variables relevant to grasp success. Given this premise, grasping becomes a process of successive exploitation of environmental constraints, until a successful grasp has been established. We present support for this view by analyzing human grasp behavior and by showing robust robotic grasping based on constraint-exploiting grasp strategies. Furthermore, we show that it is possible to design robotic hands with inherent capabilities for the exploitation of environmental constraints.

## 1 Introduction

Humans are excellent graspers. Despite decades of research on robotic grasping, we have yet to establish the same level of competency in robotic systems. What lets humans grasp so well? There are many answers to this question, most are associated with active research areas in robotics. In this paper, we explore the hypothesis that human grasp performance is to a significant extent the result of carefully orchestrated interactions between the hand and the environment. We investigate how this hypothesis may impact the development of versatile robotic grasping systems.

The premise of the work reported in this paper is the following: *A competent grasper must exploit constraints present in the environment by employing physical contact so as to counteract uncertainty in state variables most relevant to grasp success.* If this premise is true, robust and versatile grasping is the process of determining sequences of motions to leverage these constraints in the most effective manner.

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Video recordings of human grasping provide immediate support for our premise. Human grasps routinely involve contact with the environment. However, we are not aware of systematic studies on the use and purpose of such contacts in the psychology literature. In this paper, we begin to close this gap by reporting on novel human grasping experiments. We establish a set of parameters to characterize contact with the support surface during grasping. And we present human grasping studies to show that the use of environmental constraints increases with the human's uncertainty about the environment. We view this as experimental support for our premise.

Ongoing research on robotic grasping provides further support for our premise. Novel gripper and hand designs often include compliant materials or actuators. In our view, this does not only lead to more robust interactions between hand and the grasped object, it also facilitates the exploitation of environmental constraints. There are several studies of novel hands, reviewed in the next section, that deliberately exploit environmental constraints in specific application scenarios or for specific grasps. Research in grasp planning also has begun to leverage environmental constraints, however, either to a limited extent or in specifically tailored approaches. Beyond these instances, to the best of our knowledge, there is no comprehensive approach for the generic, orchestrated use of environmental constraints in robotic grasping.

In the remainder of this paper, we outline the beginnings of an integrated research agenda towards robotic grasping by leveraging environmental constraints. This agenda spans the study of human grasping, the development of appropriate grasp strategies, the required perceptual strategies to determine when which strategy is most appropriate, and also the design of robotic hands tailored for the exploitation of environmental constraints.

## 2 Background

To support our claim, we divide related work into three categories based on the types of interactions they consider. The first category, which marks the beginnings of grasping research in robotics, analyzes static grasps. The second category leverages interactions between hand and object. The final and most recent category leverages interactions between hand, object, and environment, enabling the consideration of environmental constraints for robust grasping.

### *2.1 Force and Form Closure*

Early grasping research emphasizes the concepts of force and form closure, reflecting a static grasping relationship between hand and object. A grasp is commonly expressed as a set of disembodied point contacts. Physical interactions occurring during the grasp—and sometimes even the limitations that result from the kinematics of the hand—are often not accounted for during grasp planning. These approaches require detailed models of both the environment and the hand.

This line of research continues to be active and successful, as evidenced by a large number of sophisticated and capable grasp planners and simulators [19]. In our experience, however, the grasps determined by these approaches do not reliably transfer to the real world. To provide adequate hardware for the precise placement of specific contact points on objects, researchers designed mechanically complex, rigid hands with many degrees of freedom [13].

Early studies of human grasping also followed this static view. This is reflected in grasp taxonomies, classifying grasp according to the final hand posture attained after the grasp process is completed [5, 11]. Even the early work on postural synergies, which has had a profound impact on robotics, initially only considered synergies of static grasp postures [22]. These studies do not capture the dynamic processes and the exploitation of environmental constraints we believe to be crucial for robust grasping.

### *2.2 Interactions Between Hand and Object*

During grasp execution, mechanical compliance in the hand leads to an adaptation of the hand's configuration to the object's shape. This shape adaptation aids grasp success by compensating for uncertainties in actuation and world model, and by attaining a large number of contact points. Thereby shape adaptation significantly increases the chances of achieving force closure with a grasp. Much of the recent work in robotic grasping attempts to leverage this effect explicitly.

Rodriguez et al. [21] optimized the shape of non-compliant fingers to yield the same contact point configuration irrespective of object size. Shape adaptability can be enhanced by adding compliant parts [14]. The positive pressure gripper [1] represents an extreme case in this regard. It uses granular material to achieve compliance of the entire gripper to large parts of the object's geometry.

An effective way of achieving shape adaptability is underactuation. The SDM hand [8], the Velo gripper [4], and hands by Grioli et al. [12] couple the actuation of degrees of freedom using tendon-pulley systems, adapting the shape of the hand to the object while equalizing contact forces.

The nature of hand-object interaction has also been studied in humans. While the effect of shape adaptability is well known for human hands, studies elucidate the degree to which humans vary their behavior to take advantage of it. Christopoulos et al. [3] showed that humans react to pose uncertainty of a cylinder and orient their hand to align it, presumably to be able to maximize the benefits of shape adaptability. However, other experiments may point at the fact that humans also rely on more complex interactions with the environment for grasping under difficult conditions. When the vision of humans is impaired, they fail more often at first grasp attempts of isolated (environmental-constraint free) objects [18]. The degree of the demonstrated effect seems surprising. We believe that in this specific experiment, it is due to the lack of environmental constraints exploitable for grasping.

### *2.3 Interactions Between Hand, Object, and Environment*

Features in the environment may constrain the motion of hand and object. This is most evident for supporting surfaces, such as tables and floors. These constraints, when used properly, can aid grasping. Furthermore, we postulate that the necessary perceptual information for leveraging such constraints is often easier to obtain than the information required for the successful execution of an unconstrained grasp.

Recent research in robotic grasping leverages environmental constraints in the suggested manner. These works use environmental constraints for example to position the hand relative to the object [6], to cage objects [17, 6, 20], or to fixate an object during planar sliding [7, 6]. Some pre-grasp manipulation relies on environmental constraints to improve grasp success. For example, Chang et al. [2] rotate pans to put handles into a certain orientation, prior to executing a grasp.

All of the aforementioned grasp strategies rely on multiple interactions prior to establishing force closure for the final grasp. These phases often are designed to reduce uncertainties in specific variables relevant to grasp success.

The study of human grasping behavior, as far as the exploitation of environmental constraints is concerned, so far has been limited to the replication of behavior observed by roboticists [15, 2]. We hope to lay the groundwork for a more rigorous examination of this aspect of grasping.

We believe that this recent trend towards the exploitation of environmental constraints represents an important opportunity to improve robotic grasping capabilities. To take full advantage of this opportunity, we should understand the strategies humans employ, transfer them to robotic systems, and develop robotic hands tailored to this exploitation.

## 3 Environmental Constraints in Human Grasping

In this paper we argue that competent grasping exploits constraints in the environment. In this section, we describe our work towards the identification of successful strategies for the exploitation of environmental constraints in human grasping. In a first step, we define operational measures to quantitatively characterize the exploitation of a specific environmental constraint, namely the support surface of a grasped object. We also show that the interaction with the support surface becomes more pronounced when grasping is made more difficult by impairing human vision. We view this finding as support for our main premise.

### 3.1 Quantifying Contact Interactions with Support Surfaces

We choose the following parameters to quantify the contact interaction with the support surface during a grasping trial: the number of distinct support contacts, $N$, the mean travel distance of all support contacts, $\overline{d}$ (spatial extent of contact interaction), the mean duration of all support contacts, $\overline{\Delta t_c}$ (temporal extent), and the maximum force exerted orthogonal to the support surface, $f_{max}$ (energetic extent). Additionally, we measure the grasp duration $\overline{\Delta t_g}$, i.e. the time elapsed between the first contact with either the object or the support surface and object lift. We will show that these parameters serve as a meaningful characterization of the interaction with the support surface.

### 3.2 Experiment

Five right handed adults (aged 20-25 years, two females) participated in the experiment. They were naive to the rationale behind the experimental design. All participants reported normal or corrected-to-normal vision.

A grasp trial began with the participant's hand extended and resting at a start position, see Fig. 1. An object was placed at a fixed location on top of a tablet computer located behind an occlusion panel blocking the participant's view. Then, the occlusion panel was removed and the participant was able to observe the scene. After a delay of three seconds, the participant received an auditory signal to grasp the object. During the grasp, the tablet computer recorded $N$, $\overline{\Delta t_c}$, and $\overline{d}$, see Fig. 3. The trial ended with another auditory signal, in response to which the participant to released the object and to return the hand to the start position. A force/torque sensor was attached to the tablet to determine contact with the object or the support surface, and to measure $f_{max}$. Finally, a camera was used to detect object lift.

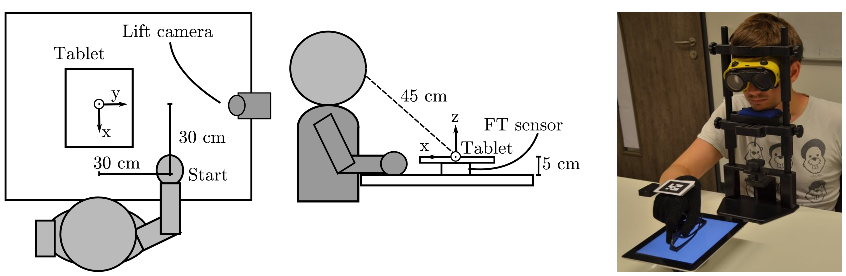



Fig. 1: Experimental setup

The experiment was performed under two conditions: control and impaired. In the control condition, human vision was not altered. In the impaired condition, participants wore custom goggles that blurred details of the objects' shape and degraded

Fig. 2: From left to right: the target objects, the blurring goggles, and the target objects as seen through the goggles

depth perception, see Fig. 2. It is difficult to quantify the effects of the goggles, but they allowed to induce a consistent and severe reduction in human vision. The impaired condition trials preceded the control trials to prevent participants from observing the details of the object shapes. Each participant performed 100 trials: ten objects, five repetitions per object, each under two conditions.

We used the following objects: a button, a salt shaker, a roll of adhesive tape, a match box, a marker pen, sunglasses, a comb, a plastic screw, a toy, and a chestnut. All objects were painted black to remove color cues for distinguishing them and to homogenize the contrast with the surroundings (see Fig. 2). The participants wore a conductive glove to improve the reliability of the touchscreen measurements. Participants were seated as shown in Fig. 1, with their head supported by a head and chin-rest. The viewing distance to the center of the tablet was 45 cm.

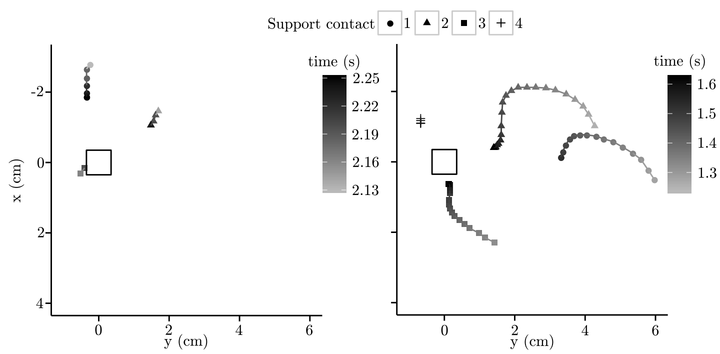



Fig. 3: Examples of the measured support contacts when grasping a screw; left: control condition; right: impaired condition. The participants were located in the positive direction of the $x$ axis, see Figure 1. The black square indicates the object's initial position. Support contacts occurred within a time interval of $\approx 0.12$ s and $\approx 0.4$ s in the control and impaired conditions, respectively

### 3.3 Results

The parameters N, $\overline{\Delta t_c}$, $\overline{d}$, $f_{max}$, and $\overline{\Delta t_g}$ measured in the five trials for an object were averaged for each participant. We performed two kinds of analyses: a correlation analysis and a series of tests for possible effects induced by the impairment.

The correlation analysis was performed based on the following reasoning: given that the chosen parameters are supposed to quantify different aspects of the same phenomenon, their inter-correlations should be high. Fig. 4 depicts the Pearson correlation coefficients in a cross correlation matrix for all five parameters in the control and the impaired condition. There were differences between the two conditions. Further analysis suggests that those differences were due to different variances of the parameters between both conditions.

In the second part of our analysis, we tested if the magnitude of the chosen parameters was significantly larger in the impaired condition. A one-tailed paired $t$-test (Holm-Bonferroni corrected, and global $\alpha = 0.05$) revealed significant effects for all parameters and for all participants.

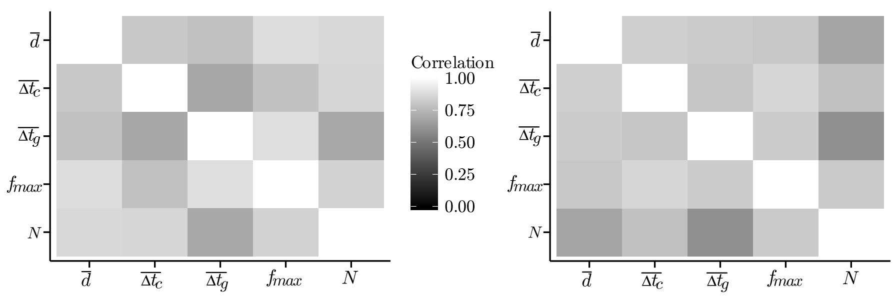



Fig. 4: Pearson's correlation coefficients averaged over all subjects; left: control condition; right: impaired condition

### 3.4 Discussion

The results of our study support two conclusions. First, the proposed parameters are meaningful for the characterization of the interaction with the support surface, as they exhibited high inter-correlations. Second, humans increase the interaction with the support surface when their vision is experimentally impaired as indicated by significant differences in the measured parameters between the two conditions. This is consistent with the main premise of this paper, i.e. that robust grasping should exploit environmental constraints to compensate for uncertainty. In our experiments, the visual impairment results in an increase in the number of support contacts, and an increase in the duration of support contacts and in their travel distance. Furthermore, the participants apply higher contact forces in the impaired condition. The grasping time in the impaired condition also increases significantly. Traditionally, in the study of human grasping, increased grasping time is interpreted as increased use of tactile feedback [18, 10]. We indeed noticed that in some trials, in particular under the impaired condition, the participants established and maintained contact with the support surface while still reaching for the object. This use of a environmental constraints, while not part of this study, can also be viewed as support for our premise.

This initial study is a first step towards a more detailed analysis of human strategies for exploiting environmental constraints during grasping. Our goal in this line of research will be to identify successful exploitation strategies and to characterize the conditions for which they are successful. We hope to transfer these insights to robots so as to endow them with improved grasping capabilities.

## 4 Exploitation of Environmental Constraints by Robots

In the previous section, we concluded that humans increase their use of an environmental constraint in response to perceptual uncertainty. In this section, we investigate how robots can exploit such constraints. Exploitation can be performed by devising appropriate grasping strategies or by designing hands tailored for this purpose. We report on our work in both of these areas.

### *4.1 Grasp Strategies*

Our goal is to design grasp strategies that exploit environmental constraints to increase grasp success and to show that there are a variety of environmental constraints that can be leveraged by those strategies.

#### 4.1.1 Exploiting Environmental Constraints Increases Grasp Success

We compare two grasp strategies that leverage the same environmental constraint to a different degree. The environmental constraint in this experiment is provided by the supporting table surface. As the height of objects decreases, grasping becomes more difficult. We expect grasp success to be higher if the constraint provided by the table surface to guide finger placement on the object is exploited to a higher degree.

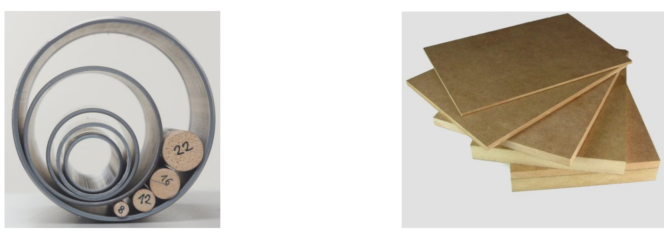
**Constant wrist pose:** The first strategy was introduced in our prior work [9]. Grasp poses are generated by fitting geometric primitives like cylinders, spheres, and boxes to depth measurements of the scene. To increase the likelihood of grasp success, pre-grasp poses are refined in response to environmental constraints. For this strategy, the palm of the hand is aligned with the support surface. The hand is then positioned as low as possible above the support surface so that the fingers do not contact the surface during closing. This strategy uses the environmental constraint provided by the support surface to position the hand but does not exploit contact interactions.

**Force-compliant closing:** The second strategy uses force control to establish contact of the fingertips with the support surface and proceeds to slide the fingers along the surface during closing, maintaining constant contact force by compliantly repositioning the wrist (see Fig. 5). Kazemi et al. [17] present a similar strategy; while they control orientation based on force feedback, we employ visual feedback.

The main difference between the two compared strategies is that the first only attempts to come as close as possible to the surface using RGB-D information about the scene, whereas the second maintains physical contact with the surface throughout the whole grasp. The same environmental constraint—the table surface—is exploited visually in one and haptically in the other.

Fig. 5: Force-compliant closing strategy, from left to right: positioning using visual feedback, contacting table surface using force feedback, closing fingers using position feedback while wrist is force-compliant in $z$-direction (last three images)

To evaluate the strategies we placed different sized cylinders (see Fig. 6a) on a table in front of a 7-DOF WAM equipped with a force-torque sensor and a Barrett Hand BH-262. All experiments reported in this section are averaged over five trials.



(a) Cylinders with 8, 12, 16, 22, 32, 40, 50, 75 and 110 mm

(b) Blocks with height 3, 6, 10, 19 and 29 mm and weight 79, 158, 233, 451, and 684 g

Fig. 6: Objects used in grasping experiments

Fig. 8 shows grasp success as a function of cylinder diameter. While big cylinders could be grasped reliably with both strategies, the grasp of smaller cylinders only succeeded with force-based exploitation of the environmental constraint. Strategy 1 causes the finger tips to hover slightly above the surface when contact with the object is made, due to the circular trajectory during hand closure. This insufficient exploitation of the surface constraint leads to a reduced success rate for small-sized objects. In contrast, the force-compliant finger closing uses the surface constraint at all times to position fingertips as close to the table as possible. Grasp success is not perfect though, as the cylinders can easily roll off the fingertips. An example of this failure mode is shown in Fig. 9a.

This experiment shows that exploiting a surface constraint to a higher degree leads to more robust grasping.

#### 4.1.2 Exploiting different Environmental Constraints

We want to show that there are multiple environmental constraints that can be exploited. To achieve good grasping performance in a variety of settings and for diverse objects, it is then necessary to employ the most appropriate strategy. The multitude of available constraints also necessitates perceptual capabilities to distinguish situations in which one strategy should be preferred over the other. To make this point, we implemented the slide-to-edge strategy and compared it to the previously presented force-compliant finger closing.

**Slide-to-edge:** The slide-to-edge strategy exploits a surface and an edge feature in the environment. It contacts the object using the the surface, slides it towards an edge, and wraps the thumb around the protruding part of the object to establish a grasp. The different phases of our slide-to-edge strategy are illustrated in Fig. 7. This strategy can also be seen as a distinct pre-grasp interaction which reconfigures the object enabling contact on parts of it that were previously inaccessible. A similar strategy was presented in [16], focusing on the planning of feasible motions.

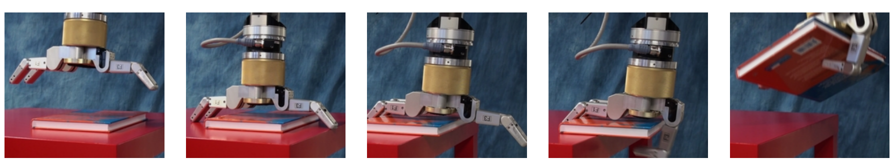


Fig. 7: Slide-to-edge grasp strategy, from left to right: positioning using visual feedback, contact surface using force feedback, moving towards the edge while being force-compliant in the $z$-direction of the wrist, closing the thumb when the hand is above the edge (detected via visual feedback), and lifting.

We evaluated the slide-to-edge strategy by comparing it to the force-compliant closing strategy for different sized blocks (see Fig. 6b) placed on a table as before. For all blocks, the slide-to-edge strategy achieves reliable performance (see Fig. 8), whereas the force-compliant strategy is only successful for flat blocks.

The slide-to-edge strategy is less sensitive to variation in the size and weight of the blocks. The flat and wide shape of the blocks enables the robot to move parts

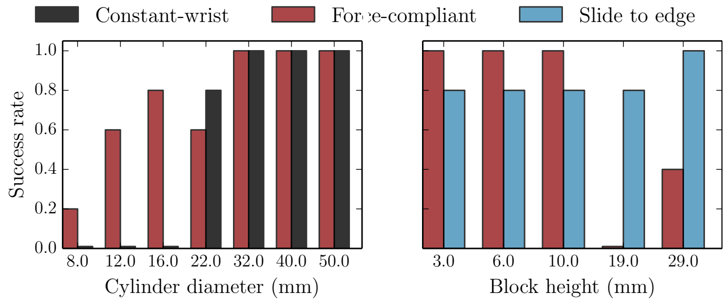
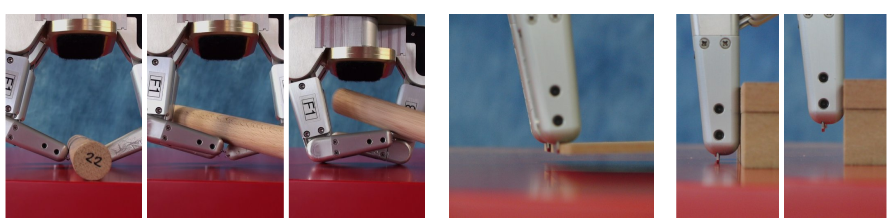



Fig. 8: Comparison of the three grasping strategies

of them over the edge, creating the opportunity to perform a more reliable grasp on the shorter side of the block. Failure cases for the slide-to-edge strategy included wrong tracking during the visual servoing positioning, missing object contact during sliding, and premature thumb closing.

The force-compliant strategy succeeds when the fingernails jam against one of the block's sharp edges, as can be seen in Fig. 9b. This is achieved consistently for the smaller blocks. For taller blocks, the fingernails do not contact the object, leading to slip and grasp failure, as seen in Fig. 9c. In a few cases, however, the nails caught the object just before slipping out of the hand. While these cases are counted as grasp success in our experiments, one should note that the intended grasp was not achieved. Success must be attributed to coincidence and the design of the finger nails.

The experiment demonstrates that different ways of exploiting environmental constraints succeed under different conditions. It also shows that the success of exploiting environmental constraints depends object characteristics in non-trivial ways. It is therefore desirable to employ a variety of grasp strategies for which the conditions of success have been characterized. Perceptual skills then must classify environments according to which of the strategies' conditions of success are met best.



(a) Failure due to object's inertia (b) Chance success (c) Failure due to slip

Fig. 9: Exemplary failure and success cases for the force-compliant closing strategy

## *4.2 Hand Design*

In this section we present our initial efforts to design a hand specifically for the exploitation of environmental constraint during grasping. If indeed exploitation of environmental constraints enables robust grasping, such hands should lead to improved grasping performance.

Environmental constraints can be exploited most effectively through contact. We therefore design hands so as to attain and maintain contact without the need for sophisticated sensing and control. We achieve this through the extensive use of underactuation and passive compliance.

Our previously presented RBO Hand is shown in Fig. 10 [6]. It employs pneumatic continuum actuators in three fingers and has two deformable pads that form the palm. The hand is highly robust (does not fail after thousands of grasps), can withstand blunt collisions, is inherently safe, and easy and cheap to manufacture. And it achieves very robust grasping performance on objects with widely varying geometries, without sensing or control, simply by inflating the continuum actuators (see Fig. 10, a more detailed experimental evaluation for these objects can be found in reference [6]). We obtain these desirable properties at the expense of precise position or force control.

Fig. 10: RBO hand and a selection of objects it can grasp

### 4.2.1 Surface-constrained grasp with the RBO Hand

Grasp strategies should take advantage of the hand's ability to compliantly attain and maintain contact with the environment. We presented such a strategy, the surface-constrained grasp, in prior work [6]. This strategy, illustrated in Fig. 11 and for a particularly difficult object in Fig. 12, makes extensive use of the environmental constraints provided by the support surface. It uses contact between the palm and the support to level the hand with the object. The fingers slide along the support to establish reliable contact with the object. Finally, the fingers adapt to the shape of the object to establish a robust grasp. These ways of exploiting environmental constraints are facilitated by the hand's design and do not require sensing or control.


Fig. 11: Execution of a surface-constrained grasp, from left to right: approach phase, exploitation of table to position and orient the hand, the fingers pull the object across the constraint surface, compliance achieves large contact area, and object lift

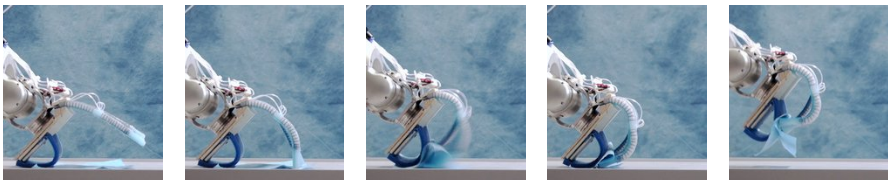


Fig. 12: Surface constrained grasp picking up a piece of tissue, from left to right: exploitation of table to position and orient the hand, exploitation of table to ensure contact with the flat object, compliant grasping, established grasp, and object lift

### 4.2.2 Slide-to-edge grasp with RBO Hand

We implemented the slide-to-edge grasp from Sec. 4.1.2 using the ROB hand. An execution of this strategy is illustrated in Fig. 13. In the first phase, the hand's palm establishes contact with the edge, eliminating position uncertainty. Subsequently, the fingers are flexed and the fingertips establish contact with the table, achieving caging. The hand rotates about the edge/palm contact to ensure contact between the fingers and the support surface, while the the compliant fingers slide along the support surface until a grasp is established. Finally, the hand retracts from the edge at an angle of 15°, lifting the fingertips from the surface and detaching the palm form the edge at the same time.

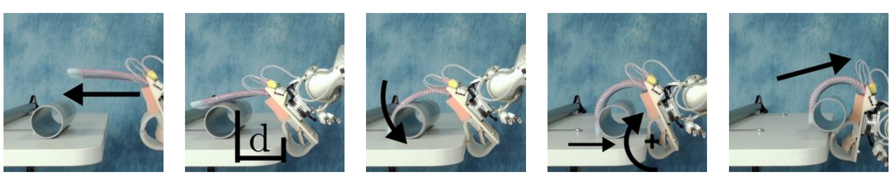
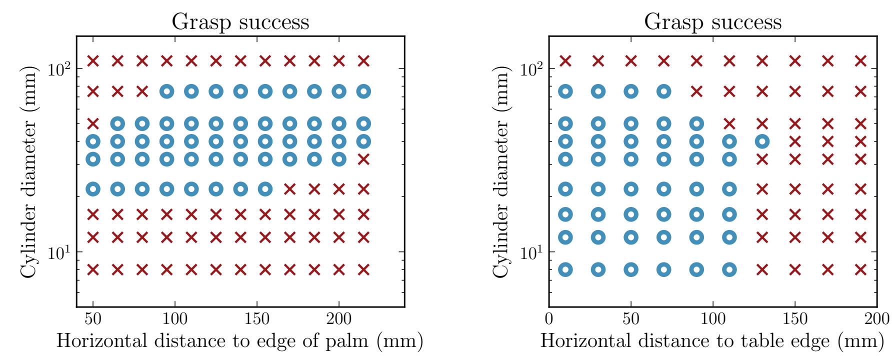



Fig. 13: Edge grasp with the RBO hand, from left to right: approach, compliant contact with the edge, sliding object along surface, sliding fingers along surface, and lift

### 4.2.3 Experiments

In previous work, we demonstrated the ability of the RBO hand to grasp a diverse set of objects of comparable size (see Fig. 10) [6]. We now complement these experiments by evaluating grasp performance with objects of widely varying sizes. We compare the previously published surface-constrained grasp with the novel slide-to-edge grasp. In all experiments, we measure the hand's ability to exploit environmental constraints during grasping by characterizing the region of success under systematic displacements of the object relative to the hand. We consider tolerance to significant displacement as a sign of good constraint exploitation.

In our grasping experiments, we used the set of cylinders shown in Fig. 6a. The set of blocks from Fig. 6b cannot be grasped by the current hand design due to limitations in actuation and hand aperture. Objects were displaced along one axis in twelve (ten) 200 mm increments, using nine different cylinder sizes, for a total of 108 (90) trials for the surface-constrained (slide-to-edge) grasp. To create a dense spatial coverage with a feasible number of experiments, every position was sampled only once for each object size.




(a) Surface-constrained grasp. Distance measure as indicated in Fig. 11

(b) Slide-to-edge grasp. Distance measure as indicated in Fig. 13

Fig. 14: Grasping results for cylinders of varying sizes and varying horizontal displacements: circles indicate grasp success, crosses indicate failure

The results of these experiments are are shown in Fig. 14a. Both strategies achieved grasp success in large and contiguous areas of the explored parameter space. Consistent grasp success under significant variations in object size and placements is a strong indication for the robustness of constraint exploitation provided by the hand design. Note that the hand does not use sensing or control to achieve this grasping performance.

The results in Fig. 14a also show that the grasps are successful under different conditions. The surface-constrained grasp requires cylinders to be at least 22 mm in diameter, whereas the edge grasp requires the presence of an edge within about

100 mm of the object. This confirms the results from Section 4.1.2 and further emphasizes the necessity of employing multiple strategies in response to the specific grasp problem.

Our experiments show that hand design targeted to exploit environmental constraints can lead to robust grasping performance for a variety of object shapes and sizes without the need for sensing and complex control. This advantage, however, comes at the cost of dexterity. The low number of actuators renders the precise control of finger forces, as required for in-hand manipulation for example, very difficult. We will explore in future research if it is possible to strike a good balance between passive compliance for constraint exploitation and detailed control for dexterous manipulation.

## 5 Conclusion

The work presented in this paper describes the early stages of an integrated research agenda in robotic grasping. This agenda combines the study of human grasping to identify strategies and principles leading to their excellent competencies with the transfer of these principles to robotic grasp planners as well as to robotic hand design.

Informed by a growing body of research in robotic grasping, we formulated the premise that robust and reliable grasping must exploit environmental constraints during the grasping process. In support of this, we presented experiments to show that humans respond to increased difficulty in the grasping problem by increasing the amount of exploitation of environmental constraints. We believe that the study of human exploitation strategies will provide important insights into how robotic grasping algorithms can achieve robust grasping performance. Following this motivation, we presented several such strategies on two different robot platforms. Each of the strategies was tailored to exploit constraints commonly present in real-world grasping problems. We demonstrated the success of constraint exploitation in real-world grasping experiments. Finally, we demonstrated the utility of designing hands to facilitate the exploitation of environmental constraints by presenting a mechanically compliant and highly deformable hand. This hand robustly grasps objects of varying sizes and shapes, without the need for explicit force sensing or feedback control.

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