Coordination of Intrinsic and Extrinsic Degrees of Freedom in Soft Robotic Grasping

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***Abstract*— We demonstrate that moving the wrist while the fingers perform a grasp increases performance. The coordination shapes the interactions between the fingers, the object and its environment to extend the hand capabilities (e.g. higher payload and precision). We evaluated our hypothesis with a human grasping study where the volunteers grasped objects by moving the soft RBO Hand 2 while its fingers closed in a predefined motion. We limited their ability to coordinate their motion with the finger movements using a compliant robot attached to the hand, and observed that their grasp success decreases with increased constraints. We also successfully transferred one of the observed movement patterns to the robot, indicating that adaptive intrinsic/extrinsic motion increases robotic grasp performance as well.**

I. Introduction

Underactuated hands exhibit outstanding grasping and manipulation performance [1]–[3], often outperforming fully actuated hands. Similarly, in the human hand, the actuation space is much lower-dimensional than the configuration space [4]. What is the benefit of this underactuation?

Both in robots and in humans, underactuation enables the hand to comply to external forces. This means that the "extra" kinematic degrees of freedom in underactuated hands do not have to be (and in fact cannot be) controlled directly—they are actuated through the interactions of the hand and the environment. Ideally, these interactions should cause motion in the extra degrees of freedom that supports grasping and manipulation.

We hypothesize that actively shaping the interactions between hand and environment contributes importantly to grasp success in underactuated hands. Furthermore, we hypothesize that this shaping can occur through the coordination of wrist motion and finger motion. Simply put: By moving the wrist while performing a grasp, we can improve the capabilities of the hand. As a first step in studying the coordination of wrist and finger motion, we examine whether and under which circumstances changing the pose of the wrist during a grasp is beneficial to grasp success. In the remainder of the paper, we refer to the degrees of freedom (DOFs) determining the wrist pose as *extrinsic* and to those that cause motion of the fingers relative to the wrist as *intrinsic* DOFs.

We validate our hypothesis by performing experiments with humans teleoperating an underactuated hand, as shown in Figure 1. We want to leverage the humans' intuition and experience in sophisticated grasping and manipulation to expose successful wrist/finger coordination strategies. Our key insight is that it is indeed possible to extend the capabilities of an underactuated hand through coordinated movement of extrinsic and intrinsic degrees of freedom. We also observe that the number of feasible coordination sequences increases when the subjects exploit contact with the environment. We demonstrate that the observed coordination schemes can successfully be transferred to autonomous robotic grasping.

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Fig. 1: A subject grasps an apple with the underactuated RBO Hand 2. The experimenter can only change the wrist motion but not the motion of the fingers. The success of grasping depends on the coordination of wrist and finger motion.

II. Related Work

We review the relevant literature in two parts. First, we present grasp planners with increasing levels of intrinsic/extrinsic coordination. Second, we provide a brief review of the human grasping studies and describe the efforts and challenges in transferring coordination insights to robots.

A. Coordination in Grasp Planners

Classic grasp planners [5], [6] compute contact points on a given object to which applying forces/wrench would lead to stable grasps. The overall motion strategy is to have the hand assume a fixed pose, then close the fingers, and then retract the hand. In this process, the hand and the fingers are generally not moved at the same time, and there is no mechanism to adapt the extrinsic DOFs according to the movement of the intrinsic DOFs. Therefore, the robustness of this strategy depends on the precise control of the fingers and perception of the object geometry. However, Weisz et al.

[7] have shown that these strategies prove to be unreliable under small disturbances to either control/precision modules.

An alternative view is to treat grasping as a dynamic process where the manipulation of the objects before and after the hand movement also contributes to the grasp success. Eppner et al. [8] used pre-grasp movements to reposition an object in the scene where the grasp can be realized with maximum likelihood. These strategies, named as *environmental constraint exploitation*, utilized features of the environment (e.g. the edge of a table, the corner of a wall) to cage and grasp objects. Chang et al. [9] used a similar approach to reorient objects with handles towards the robot. Regarding manipulation after hand closure, Berenson et al. [10] demonstrated this notion to grasp heavy objects. Their motion planner first pulls the object closer to the robot and then lifts it to avoid torque limits. The common drawback of these strategies is that they do not *adapt* to the interactions between the hand, the object and the environment.

Finally, there are examples of specialized planners that exhibit tighter coordination between the movement of the fingers and the hand. For instance, Dafle et al. [11] used a sequence of consecutive intrinsic and extrinsic movements to perform in-hand manipulation. Kazemi et al. [12] proposed a feedback control for the hand position to ensure the fingertips stay in contact with the table while closing. Coordination was explored in dynamic object manipulation as well, for instance to throw a ball [13] or to prevent objects from slipping [14].

B. Transferring human grasping skills to robots

Similar to the early work in grasp planning, initial human grasp studies focused on the position of the fingertips on an object [15]. Although there have been attempts to transfer human hand postures to robot hands, the efforts have been nevertheless limited by the robot capabilities [16], [17]. Instead, recently there has been a shift of focus onto pre-grasp strategies. Kazemi et al. [12] observed that when people grasp small objects, they first contact the table and then use its guidance to slide the fingers towards the object. Eppner et al. [8] and Heinemann et al. [18] generalized these observations to a taxonomy of strategies based on the intrinsic and extrinsic movement of the hand and the contacts created with an object and its environment. The transfer of these insights have led to increased robotic grasp success.

In general, the human demonstrations that incorporate the hand's intrinsic properties are more relevant to robotic transfer because a mapping across morphologies is no longer needed. Balasubramanian et al. [19] pursued this approach to compare operator-driven grasps of a robotic hand with autonomously generated static approaches. They observed that the operator's manipulation of the extrinsic DOFs, specifically the hand orientation, was a key factor in their superior performance. In this work, while we similarly use robotic hands, we broaden the investigation to include pre-grasp and post-hand-closure strategies and utilize robot arm kinematics to study human coordination patterns.

It should be noted that while the coordination between the intrinsic and the extrinsic DOFs of human hands have been studied during the approach phase of a grasp, the necessity of the coordination, particularly during the manipulation of the object in grasping, is still under review [20].

III. Experimental Design

To study coordination of the intrinsic and the extrinsic DOFs of soft robotic hands, we set out to leverage the experience and the intuition of humans in grasping. In the following, we first describe the experimental setup where the key ideas are (1) to have the subjects use a robotic hand and (2) to alter their coordination capabilities with a compliant robot arm. Secondly, we describe how the experimental conditions limit coordination with increasing levels of constraints on the hand's extrinsic DOFs and during different phases of a grasp.

A. Experimental Setup

Seven right-handed volunteers with no prior knowledge of the research hypothesis participated in the experiment and gave their informed consent to the protocol. An experiment lasted for about four hours and was conducted in two sessions. The subjects stood in front of a glass table upon which objects were placed at fixed poses. They used the RBO Softhand 2 [3], attached to a hollow plastic stick, and closed the fingers simultaneously in 2.5 seconds with a remote. In some experiment conditions, the stick was attached to a 7-DOF robot arm, Barrett WAM. The robot either (1) hovered freely in the air, (2) locked its position, or (3) executed a predefined motion to lift or to slide the object off the table. When prompoted, the subjects chose one of the two types of robot predefined motion but could not intervene.

A motion capture system and the robot encoders recorded the hand movement; while the pressure sensors in RBO SoftHand 2 tracked the finger motion. The two force/torque sensors were placed at the robot end-effector and between the hand and the stick. Four cameras recorded the scene. Figure 2 displays the objects in the order they were grasped, from the subjects' point of view. The objects were diverse in size, weight and shape, and yet graspable by the soft hand.

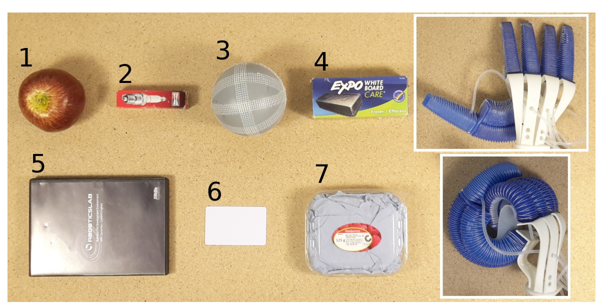

Fig. 2: Left: Object dataset: Apple, spark-plug box, ball, white board eraser, DVD box, credit card and fruit punnet. Right: The RBO Hand 2 in its open and closed states.

B. Experimental Conditions and Protocol

The control variable in the experiment was the level of constraint on the subjects' movement. The goal is to observe if and how the subject's strategy is adapted under increasing constraints on their extrinsic movement. Below, the four main conditions are listed in an increasingly constrained order:

- Hand-on-a-stick (HS): The subject moves the stick freely without robot constraints.
- Free robot (FR): The subject moves the stick attached to the robot end-effector while the robot freely moves. (Only robot kinematic constraints are imposed.)
- Locked closure (LC): Similar to *free robot*, except during only hand closure, the robot arm is locked so that the subject can not change the extrinsic state.
- Robot pick (RP): Similar to the previous case, except after hand closure, the subject instructs the robot to perform a predefined movement that either lifts the object directly or slides it off the table horizontally.

For each condition, Figure 3 visualizes the level of constraints on extrinsic movement where orange stands for kinematic constraints and red indicates that the robot has taken over the task within that phase.

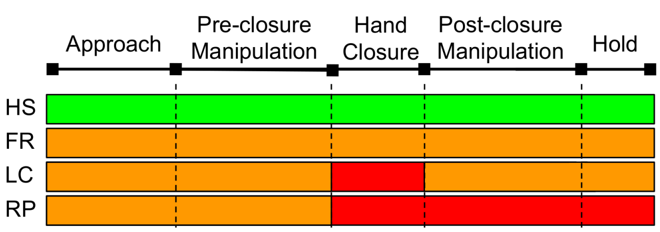

Fig. 3: Severity of the constraints on the subjects' extrinsic motion during a grasp by condition: Free (green), limited by robot kinematics (orange) and robot takes over (red).

An object was grasped in all conditions before moving on to the next one. In Figure 4, we visualize the protocol per object. Note that the constraints increase for each object throughout the experiment. To allow subjects to generate strategies for a given set of conditions, we introduced play-times of maximum 20 minutes. To observe the effect of the robot motion constraints on a particular strategy, we introduced an *interrupted locked closure* (ILC) condition, where a trial began in the *locked closure* condition but after the hand closure, the robot completed the grasp itself without relinquishing control to the subject (against their expectation). This condition is used as a baseline to observe how the subjects adapt the pre-hand-closure movements in the *robot pick* condition when they know that the robot will take over the coordination after hand closure and after they had time to develop strategies in the preceding playtime.

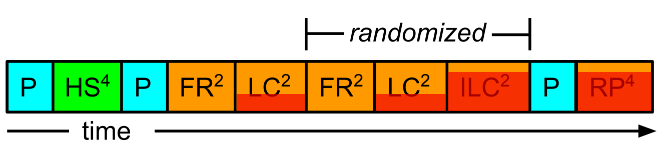

Fig. 4: Experimental protocol where the playtimes (P) are interleaved with the trials of increasingly more constrained conditions. The number of repetitions are in the superscripts.

For an object and a condition, 2-4 trials were conducted (see Figure 4) and a trial included at most three attempts. An attempt is a success if the subject can hold the object for 5 seconds, and a trial is a failure if all three fail. We performed two trials each for *free robot*, *locked closure* and *interrupted locked closure* in a random order to avoid sequence bias.

IV. Coordinated Intrinsic/Extrinsic Movement Extends Hand Capabilities

We begin our analysis by evaluating the experimental setup using the metrics: trial failures and attempt failures. While the trial failures depict whether a grasp is possible for a specific object and a condition, the attempt failures indicate how challenging it was for the subjects to demonstrate a grasp. Figure 5 plots the failure rates across conditions which are organized on the x-axis in the order discussed in Section III-B. We first note that the trial failure rate for the *hand-on-a-stick* condition is less than 1% which confirms that the objects are graspable. Secondly, the 5% bound for the trial failure rate in the *free robot* condition suggests that the compliant robot movement was a factor but not a major limitation. Lastly, although not visualized, we note that each object was grasped successfully in all trials by at least one subject in *robot pick* condition, which indicates that the robot behavior was reliable.

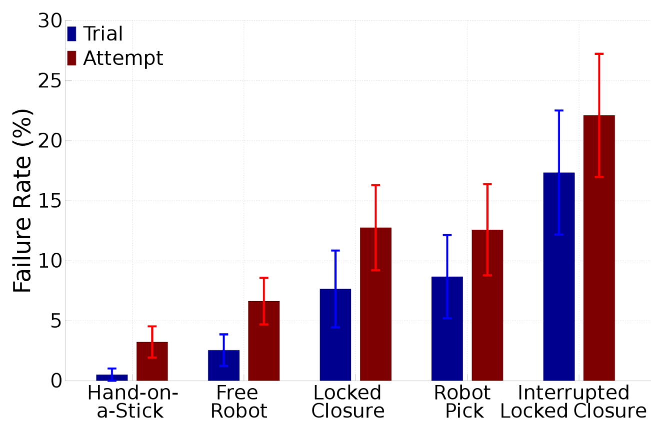

Fig. 5: More constraints on the subjects' extrinsic movement and coordination capabilities lead to more grasp failures.

Secondly, we focus on the *free robot*, *locked closure* and the *interrupted locked closure* conditions because they were conducted contiguously without a playtime in between. Therefore, the subjects presumably demonstrated the variations of the same strategy across conditions. We observe an increase in mean trial and attempt failures with increasing constraints, with at least one standard error apart, which suggests with at least 95% confidence that *the coordinated intrinsic/extrinsic movement increases grasp robustness*.

A. *Effect of object geometry*

In Figure 6, we use the more frequent attempt failures for a more nuanced analysis of the object-wise effect of conditions on success. We first note that the effect of the condition manipulation is not uniform across objects. While the failures increase drastically with the ball, we observe similar trends up to more than 20% with the card and DVD box, and 14% with the punnet. On the other hand, we see a lack of this effect on three objects (apple, plug and eraser), where their failure rates are bounded to 5% across conditions.

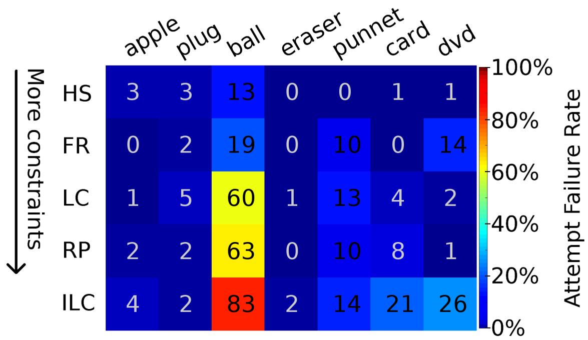

Fig. 6: The grasp robustness with respect to extrinsic constraints differs per object: apple, plug and eraser are not affected by constraints with $\leq 10\%$ failure in all conditions

Secondly, given that the ball is affected significantly more by the constrained conditions, we report on the effect of condition constraints without it as well. The trial failures for *free robot* is 60% less than the *interrupted locked closure* condition, which supports the previous analysis. However, the *locked closure* effect is inconclusive. In Section IV-B, we examine the effect of this condition for the ball case.

Three of the four objects which failed in constrained cases more often were the heaviest ones in the dataset. Two of them, the card and the DVD box, are the two thinnest ones. Finally, the dimensions of the punnet and the DVD box are close to the hand size (see Figure 2) whereas at least one dimension of the others falls well within that limit. Therefore, we observe a pattern where the objects which are adversely affected by the condition constraints are either heavier or geometrically less compatible with the pre-grasp shape of the hand. Thus, we hypothesize that *an increase in coordinated movement enables the hand to grasp a larger set of objects*.

In the next two sections, we analyze the measurement data to validate and to draw insights from the extrinsic movement within different phases of a grasp.

B. Concurrent manipulation of intrinsic and extrinsic DOFs

We first check if subjects exhibited concurrent intrinsic/extrinsic movement. We use the variance of the total hand displacement as a metric to evaluate the amount of moment as the hands close. The variances for all objects in the *free robot* condition are almost an order of magnitude larger than those in *locked closure*. This shows that subjects move the hand as it closes if they can, in the order of 3.8 ± 1.6 cm.

Secondly, we note a correlation between the variances and the susceptibility to condition constraints. The mean variance for the apple, the plug and the eraser is 1.7 cm in comparison to the 3.9 cm of the rest of the dataset. We will note such discrepancies between the groups for other phases as well.

Third, we examine the most tangible effect of blocking concurrent coordination: a 41% decrease in grasp success for the ball (see Figure 6). We hypothesize that this decrease is due to the subjects' coordinated movement of the hand DOFs for the ball object and that subjects who adopt such movements should fail more often if their coordination is limited. As a first approximation, we evaluate the Pearson correlation between the mean total hand displacement in the *free robot* condition and the decrease in success rate with *locked closure*. The outcome value of 0.82 indicates that the variables are positively correlated where 1.0 is a total fit and 0.0 is lack of correlation. Therefore, we conclude that *there exist grasp strategies that rely on concurrent extrinsic/intrinsic movements, and the restriction of this coordination leads to decreases in grasp reliability*.

C. Retraction strategies following hand closure

Grasp stability is tested as the hand retracts from the scene and the object breaks contact with the table. We hypothesize that coordinated retraction motion leads to more reliable grasps. To test this hypothesis, we devised the *interrupted locked closure* condition where a scripted robot motion supersedes a subject's intended strategy after the hand closes.

We compare the success rate for this condition with *locked closure* where the difference is that subjects execute their own retraction strategies. With the interruption, the success rates for the ball, the card and the DVD box, decrease by about 20% while the performance for the other objects are not affected (see Figure 6). Therefore, these three objects support our hypothesis that coordinated retraction enables successful grasps while for the others, we suspect the coordination in post-closure is not necessary for performance.

To identify why the role of coordination is different across objects, we analyze the rotational aspect of the hand extrinsics. We focus only on rotation because the translations, dominated by the changes in the lifted object height, may not convey additional information. We use the variance of the rotations as an indication of amount of rotational movement and use the geodesic distance between the orientations as a metric [21]. The objects with the highest increase in failures in the interrupted condition are also the ones that have the highest rotational variance in *locked closure*: the ball ($64.7°$), the card ($45.8°$) and the DVD box ($43.5°$) vs. the rest ($19.9°$). Therefore, we conclude that for some objects, the rotational movement during retraction enables their successful grasps.

The large rotational movements for the ball move the forefingers or the thumb underneath it before subjects lift it. Figure 7 visualizes one such strategy where the subject first closes the hand around the ball and then rolls it on top of the thumb so that the thumb supports the object's weight. When the subjects slide flat objects off the table, they also rotate their hand to support the objects underneath (see Figure 8).

We observe a theme across these grasps where, in contrast to classic contact-point based approaches, *the force closure of the object is achieved incrementally as the hand and the object interact with the environment during retraction*. In

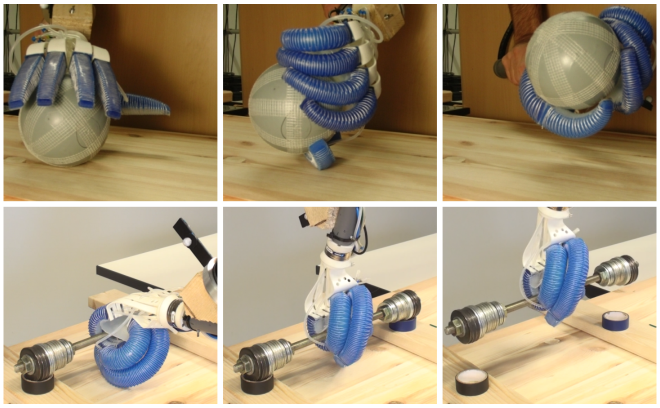

Fig. 7: Top: A subject rotates the hand to move the ball over the sturdy thumb section before lifting it. Bottom: Robot execution of the rotation strategy to shift the projection of the 1.8 kg dumbbell from the flexible forefingers towards the more rigid finger bases

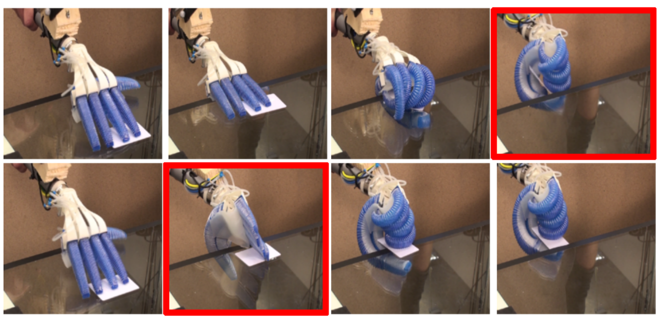

Fig. 8: Subjects used alternative coordination schemes to support the object at an edge grasp. They either first closed the hand and then rotated it (top) or vice versa (bottom).

future work, we will exploit this gradual process to detect failures early on and adapt the extrinsic DOFs appropriately.

Transfer of a coordination pattern to a robot: Given the prevalence of the rotational strategy in the post-hand-closure phase, we evaluated whether it could enhance robot grasping capabilities. We implemented the strategy as a sequence of task-space controllers where the hand performs in the following order: (1) approach object from top, (2) close, (3) roll around the object for a fixed amount, and (4) lift. To simplify the execution, we used bar-bells where the rolling motion could be executed without table contact. We evaluated the strategy incrementally with 100g weights and in four levels of rolling rotation, $\{0°, 25°, 50°, 75°\}$, where $0°$ is the classical top-down approach-close-retract strategy.

While the static approach could grasp at most 600g, the rotations of $25°$ and $50°$ scaled up to 1200g and the $75°$ motion reached a maximum of 1800g. With this controlled experiment, we observed that the main effect of extrinsic movement is to move the contact point with the object from the more flexible fingertips towards the stable bases of the fingers. Therefore, with larger rotations, the weight of the object is projected onto the sturdier parts of the hand and thus, larger weights can be grasped.

Based on these results, we believe that *extrinsic motion after hand closure enables the exploitation of the intrinsic hand properties and therefore increases its capabilities*.

We note that it is also possible to grasp the 1.8 kg weight by rotating the hand around the object before the hand closes while keeping its position stable - an example of a set of strategies we discuss next.

D. Pre-grasp manipulation of objects

The *robot pick* case mimics the classic point-contact based grasp strategies [5], [6] in that the external DOFs follow a fixed strategy during and after hand closure. The difference is that, here, the subjects can manipulate the object and choose the pose at which the hand closes. This condition follows *interrupted locked closure* and a playtime, and we are interested in if and how the subjects adapted their movement to their lack of control following hand closure.

For the apple, the plug and the eraser, all the subjects successfully demonstrated the same pre-grasp motion they performed in the other conditions: they simply approached the objects from the top and closed the hand. Note that here is yet another condition where subjects do not alter their behavior for this set of objects. For the ball, the subjects who previously pursued a rotational strategy, could not adapt their strategies within the playtime and we observed significant decreases in success rate (60%) compared to *locked closure* condition. This result reinforces our observation in the *interrupted locked closure* that the manipulation of extrinsic DOFs extends the hand capabilities to this object.

With the flat objects, four subjects changed their strategy and reached similar success rates with *locked closure*. While all four adapted their pre-grasp movement to ensure the hand reached beneath the object once the robot took over, here, we focus on one case. The subject who had previously rotated the hand during the post-closure phase in *locked closure* performed the same rotation in the pre-closure phase (see Figure 8). This behavior shows that the order of hand rotation and closure can be interchanged in this case. Given the peculiarity of being able to apply a post-closure policy to the pre-closure phase, we performed a follow-up experiment to understand this phenomenon.

Environmental constraints and coordination timing: As the thumb rotates under the table during pre-closure, the table supports the card's weight and the hand's contact forces and thus, preserves the contact between the hand and the card (Figure 8). Given that an environmental constraint enabled this reordering, we predicted that the order of hand movement and closure may be switched with a "wall" constraint. A wall was added to the scene for the subjects to confine the ball's pose and then grasp it.

With three subjects, we performed the experiment using two conditions: *robot pick* (as before) and *robot approach*. In *robot approach*, the robot pushes the ball to the wall and then the hand closes, leaving the subject the role of lifting the ball. Figure 9 displays an example of subjects' movements where they either first closed the hand (B) and then rotated it (C), or first rotated the hand (E), scooping the object within

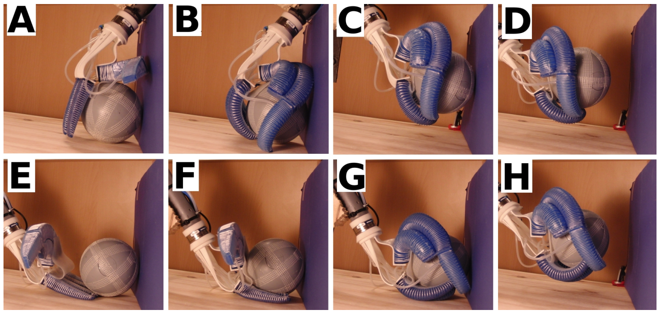

Fig. 9: Two timing alternatives (top and bottom) for grasping a ball at a wall (blue) based on whether the intrinsic or the rotational extrinsic movement comes first.

the palm (F), and then closed the fingers to secure the grasp. Note that the second strategy can only be executed with a wall against which the object can be pushed and scooped.

We observed that, while there were no trial failures, the attempt failures were 89% and 81% for *robot pick* and *robot approach* respectively. These results support our prediction that both sequences are feasible with the wall constraint. In both edge and wall grasps, during the extrinsic-first strategies, the constraint surface provides the connection between the hand and the object, which would otherwise be created only by the hand closure.

Therefore, we believe these results support the hypothesis that *environmental constraints relax the timing constraints between intrinsic and extrinsic hand movements*. In future work, we will investigate how grasp planners can exploit this increase in the number of feasible coordination patterns.

V. Conclusion

We demonstrated that, in underactuated hands, the appropriate coordination of wrist motion (extrinsic degrees of freedom of the hand) and finger motion (intrinsic degrees of freedom of the hand) increases grasp performance. In our experiments, this coordination was able to compensate for the low payload and dexterity of the fingers by shifting the weight of the objects to the sturdier parts of the hand and by interacting with the environment. We also observed that exploiting environmental constraints increases the number of feasible coordination patterns. In conclusion, the adaptive coordination of intrinsic and extrinsic hand movements extends the capabilities of underactuated hands and enables robust grasps. Finally, even though this remains to be shown explicitly, we believe that the coordinated motion of extrinsic and intrinsic degrees of freedom also offers benefits when using fully actuated hands.

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