Multi-Dimensional Compliance of Soft Grippers Enables Gentle Interaction with Thin, Flexible Objects

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***Abstract*— In this paper, we discuss the role of gripper compliance in successful grasping and manipulation of thin, flexible materials. We show, both conceptually and empirically, that each axis of compliance in a planar gripper provides unique benefits in this domain. Vertical compliance allows robust grasping of thin materials in the presence of large uncertainty in positioning. Lateral compliance increases opportunity to respond to unexpected snags by increasing the time window over which tensile forces are applied. Rotational compliance avoids damage to objects by decreasing the maximum tensile forces applied during snags. We explore these three benefits through empirical tests comparing a rigid gripper to a soft gripper, evaluating the level of vertical uncertainty each can handle for prehensile and non-prehensile manipulation, as well as the forces and displacements incurred during snags. The results show how a soft gripper's three-axis compliance provides a passive ability to prevent damage to delicate materials.**

I. Introduction

Grasping and manipulating thin, flexible objects (fabric, tape, bags, etc.) is an essential skill for robots to achieve in the home, in built settings, and more-remote environments. Assistive tasks such as folding clothes, using towels to clean messes, making a bed, and handling some foods (tortillas, pizza dough, pastry sheets, etc.) are all aspirational tasks for home-based robots. In commercial settings, robots could be used for cleaning tasks requiring handling of towels or similar implements, applying tape for packaging, etc. Looking into the future, robots could also help with autonomous protection of habitats or vehicles in remote or dangerous environments. For example, using fire blankets to extinguish a fire or applying an adhesive patch to seal leaks in undersea or extraterrestrial settings will require robots to robustly handle thin flexible materials. However, handling such materials is still challenging for modern robotic manipulators.

Several advances in robotic handling of thin, flexible objects in recent years aim to enhance the capabilities of traditional rigid robotic systems in the realms of perception, planning, and learning. For example, representing the pose of a piece of fabric or a garment presents fundamental challenges to traditional pipelines, requiring new methods for efficient geometric representations [1]. In grasp planning,

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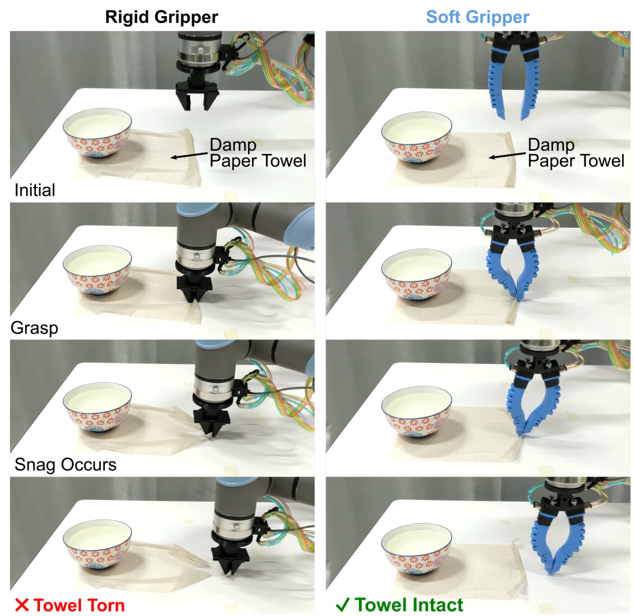

Fig. 1. Three-axis compliance enables soft grippers to gently interact with thin, flexible objects and the surfaces they rest on. Gentle interaction is especially important for delicate materials, like the damp paper towel shown here. During the grasp, the vertical compliance of a soft gripper allows for large positional uncertainty; during a snag (when the swatch is caught), the soft gripper's lateral compliance increases the time over which forces are applied, and rotational compliance decreases the maximum tensile forces applied, preventing damage. By contrast, the rigid gripper tears the swatch.

some earlier work also looks specifically at grasp planning for hemmed fabrics [2], and more-recently for handling folded fabrics [3]. For task planning, the task of making a bed was investigated using deep learning to determine where to grasp a bed sheet in order to unfold it to a desired state [4]. Finally, attempts to transfer learned behaviors to real hardware were reasonably successful for the task of hanging a sheet of fabric on a hanger [5]. However, the main limitation in the latter study was the fact the combination of a rigid robot arm and rigid gripper could only handle very small vertical uncertainty when grasping before failure.

At a higher level, Borras et al. developed a comprehensive framework for grasping and manipulating fabric that attempts to abstract away the specific gripper morphology [6]. They present a taxonomy of grasps commonly used in fabric manipulation, and demonstrate how specialized grasps can make manipulation of fabrics easier. The grasp taxonomy includes point, line, and surface contacts, and also includes the environment (tables, surfaces) as a source of extrinsic dexterity. While this framework nicely enables high-level reasoning about which types of grasps to use for a given task, our work is focused on understanding how to enable each of these grasps in a robust way through hardware design.

There has also been a recent push toward the low-level design of end effectors specifically for grasping fabric and other thin materials. A review of gripping devices for commercial fabric handling shows many purpose-built grippers used in manufacturing, while most grippers used in fabric handling research are simple two-fingered grippers [7]. Some grippers use alternative means of grasping that are particularly well-suited for fabrics and other thin materials, such as electrostatic attraction [8] and micro-needles [9]. Several grippers have also been designed based on a study of how humans grasp fabric, where key motions are extracted and robotic finger kinematics are optimized to replicate human motion [10], [11], [12]. Conversely, a top-down approach to gripper design has also been taken, designing morphology from a task-centric perspective, and leading to key innovations such as a large base for supporting fabric, and a variable-friction surface on the fingertip for sliding against substrates [13]. However, the precise role of compliance for interaction with thin, flexible objects has not been fully explored, and mitigating snags (where the swatch is caught and tensile forces are applied) has not been considered.

In this paper, we discuss the role of gripper compliance in successful, safe grasping and manipulation of thin, flexible materials. We show that for a planar gripper, vertical, lateral, and rotational compliance each contribute to preventing damage to the material. We demonstrate these benefits through an empirical case study comparing a rigid gripper to a soft gripper. We evaluated the level of vertical uncertainty each gripper can handle for prehensile and non-prehensile manipulation, and the forces and displacements incurred during snags. Finally, we demonstrated the integrated utility of three-axis gripper compliance for grasping and manipulating delicate materials, as shown in Figure 1.

II. Conceptual Grasping Analysis

Successful handling of thin, flexible objects requires both grasping and manipulating swatches of material such that no damage occurs. Many tasks require grasping swatches that initially lie flat on a surface; thus grippers must be able to gently handle contact with those surfaces even in the presence of positional uncertainty. Once a swatch is grasped, the robot must also take care not to apply large tensile forces to it, even when the material unexpectedly snags. In this section, we develop a conceptual analysis of how compliance affects grasping and manipulation success, and discuss key performance metrics related to risk of damage of swatches.

A. The Role of Compliance in Grasping

Grasping thin, flexible objects from a surface on which they rest (e.g., a tabletop) usually requires a robot to interact with that surface. Since the objects are thin, achieving point-to-point or line-to-line grasps (as defined by Borras et al. [6]) requires a robot to interact with the surface through the object, or at least operate in very close proximity to the surface. Furthermore, utilizing the resting surface plane

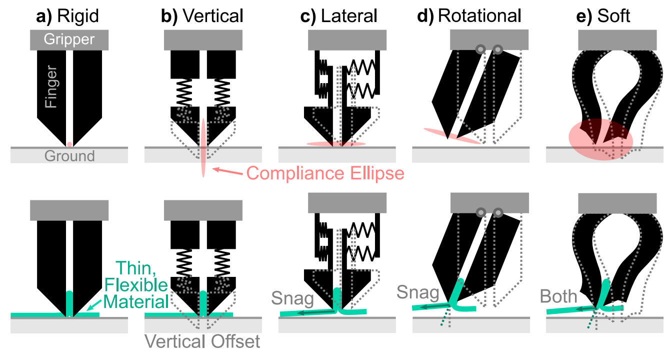

Fig. 2. Grasp compliance in three axes is critical for grasping thin objects from a surface, while also enabling snag-resistance. Five conceptual finger designs are shown which explore each axis. a) With zero compliance, the gripper is rigid. b) With only vertical compliance, the gripper passively handles vertical uncertainty. c) With only lateral compliance, the gripper has graceful snag protection. d) With only rotational compliance, the tensile force applied during a snag is redirected away from the lateral direction. e) With compliance in 3 axes, (commonplace for soft robotic grippers), the robot can natively handle vertical uncertainty and snags.

as part of an extrinsic grasp involving plane-to-point (or -line or -plane) contact explicitly relies on interaction with the surface. Thus, robustness to uncertainty in the surface's vertical position relative to the gripper is critical.

To achieve high robustness to vertical positioning error, large vertical compliance (low stiffness) in the gripper can be utilized. Such a gripper can be pressed into the table with minimal vertical force applied to the object (Figure 2b), while a rigid gripper (Figure 2a) must be placed with high precision to avoid applying large forces. Vertical compliance achieves a similar effect as hybrid position/force control, where force control is desired in the vertical axis ([14], [15]). In addition, using the table surface as part of the gripper via extrinsic dexterity is simplified by leveraging vertical compliance with that surface [16].

For a successful grasp of a thin, flexible object, we can define several damage-related performance metrics. Normal forces must be low enough to prevent denting, creasing, or wearing through the material during the grasping process, and shear forces must be low enough to prevent tearing. To consider both of these failure modes, we can define the range of acceptable uncertainty (normal to the surface) in the hand position before forces become large enough to damage a swatch. This allows us to take into account the fact that interaction forces between the table, swatch, and gripper are related to positional error.

B. The Role of Compliance During Snags

Once a swatch is grasped, the robot must prevent damage to it if a snag occurs, i.e., caught on or under other surfaces such that a tensile force is applied. Detecting and recovering from snags is especially important for delicate sheets like tissue paper, garments, dough, or pastry crusts. External sensing such as vision gives poor information about the stress state of thin swatches, especially for in-extensible materials which incur very little deformation even under large loads. To detect snags, a robot would then need to use force or torque sensing in the arm or in fingers to detect such forces, requiring high sensitivity and bandwidth to react to snags before catastrophic damage occurs.

To achieve high robustness to unexpected snags, gripper designs can utilize both high lateral compliance and high rotational compliance. Lateral compliance can be used to increase the time over which forces are applied (assuming constant wrist motion) by allowing the grasp to translate relative to the arm during a snag event (Figure 2c), giving the robot more time to detect and react to the snag. Additionally, rotational compliance enables the grasp to rotate relative to the arm during a snag event (Figure 2d), allowing tensile forces to be applied closer to parallel with the gripper. This change in direction causes the grasp to fail at a lower snag force than it would without rotation.

C. The Role of Multi-Dimensional Compliance

Based on the previous two conceptual analyses, a gripper with three-axis compliance should be robust to both vertical uncertainties and unexpected snags. One class of grippers with 3-axis (and often fully 6-dimensional) compliance is soft robotic grippers, where fingers are made entirely of soft materials. This soft construction allows such grippers to be extremely robust to a wide range of uncertain conditions in their environments, including the positions, sizes, and shapes of target objects, as well as those of obstacles and ground planes [17], [18], [19], [20], [21], [22], [23]. As such, soft grippers are particularly well-suited for handling thin, flexible objects in a gentle way, as indicated by Figure 2e.

For a given material, the compliance ellipse (planar representation of compliance) of a soft gripper should be tuned to ensure correct force thresholds are maintained for minimal damage or wear from pinching or snagging. For example, an elastic fabric can sustain large normal forces (i.e., won't dent) and large shear forces during snags, so the lower bound on compliance is small in all directions. Conversely, thin tissue paper cannot sustain large shear forces, so large vertical compliance is necessary to prevent high friction forces with the table when grasping, and high lateral and rotational compliance allows large deformation of fingers during snags.

III. Results

We demonstrate the benefits of multi-dimensional compliance for handling thin, flexible materials by performing a series of empirical investigations comparing a rigid gripper (zero compliance) to a gripper with fully soft fingers (2D compliance). The rigid gripper used was a PhantomX Parallel AX-12 (Trossen Robotics) parallel jaw gripper based on a Dynamixel AX-12 servo (ROBOTIS), with stiff foam pads on the inside surfaces of the fingers (3 mm thickness) to improve friction. The rigird gripper has vertical and lateral grasp stiffnesses of 19800±300 N m and 5200±200 N m (mean and standard deviation of $n = 3$ trials) at maximum gripping strength. The soft gripper is a custom, two-fingered, pneumatic gripper from [19] designed for pinch grasping, with vertical and lateral grasp stiffnesses of 2580±20 N m and 260±10 N m at its operating pressure of 193 kPa, controlled using a custom pressure controller previously shown in [24].

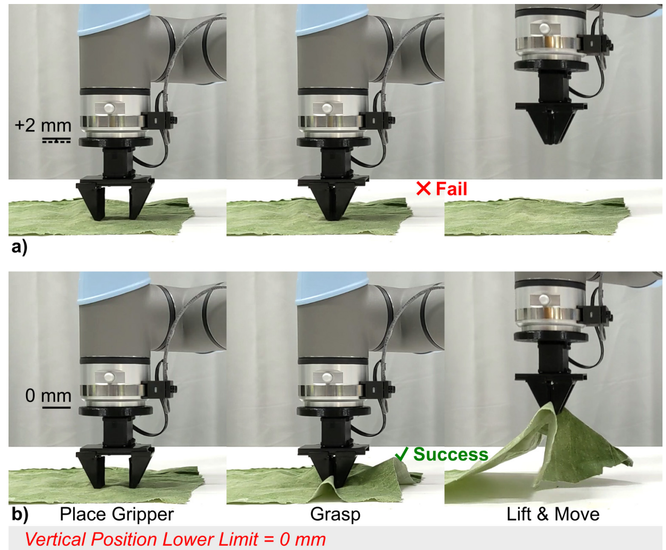

Fig. 3. For a rigid gripper attempting to grasp a 1 mm-thick swatch of fabric from a table, the region of allowable vertical uncertainty in the gripper's position is extremely small (between 0 mm and + 2 mm). Example grasp sequences are shown with fingers a) 2 mm above the table and b) touching the table. Due to the rigid construction of the gripper, the arm cannot move lower than the position shown in b).

All experiments were performed by mounting each gripper to the wrist of a UR5e robot arm (Universal Robots) set to a 150 N maximum force before the safety stop is triggered. Robot Operating System (ROS) was used to coordinate robot and gripper motion, as well as capture gripper poses using AprilTags [25] where applicable, however the actual grasping tasks were performed open-loop without the use of vision.

A. Robustness to Uncertainty During Grasping

To test the effect of vertical compliance on grasp success in the presence of uncertainty, grasps on a 1 mm thick swatch of woven cotton were performed with both grippers over a range of known vertical centering offsets. With the height where the fingertips just touch the table's surface set as the 0 mm reference point, grasps were performed for offsets ranging from 4 mm (above the table) to −40 mm (below the table), with increments of 1 mm for positive offsets and 2 mm for negative offsets. A grasp is considered successful if the arm can pick up the swatch. In these experiments, the rigid gripper was operated at maximum actuation strength (with a pull-out force of 7.4 ± 0.8 N), while the soft gripper was operated at 70% of its maximum actuation strength (with a pull-out force of 1.82 ± 0.02 N) to preserve its lifespan. Pullout forces are reported using the mean and standard deviation of $n = 3$ trials.

The results of this study demonstrate that the vertical compliance of a soft gripper greatly increases the range of allowable vertical uncertainty that can be handled compared to a rigid gripper, as shown in Figure 5. For the rigid gripper, the region where successful grasps occur is extremely small (2-3 mm total), as shown in Figure 3. Specifically, the rigid gripper fails to grasp at + 2 mm offset above the table due to insufficient contact with the swatch, as well as lower than 0 mm offset (into the table) due to large forces that trip the

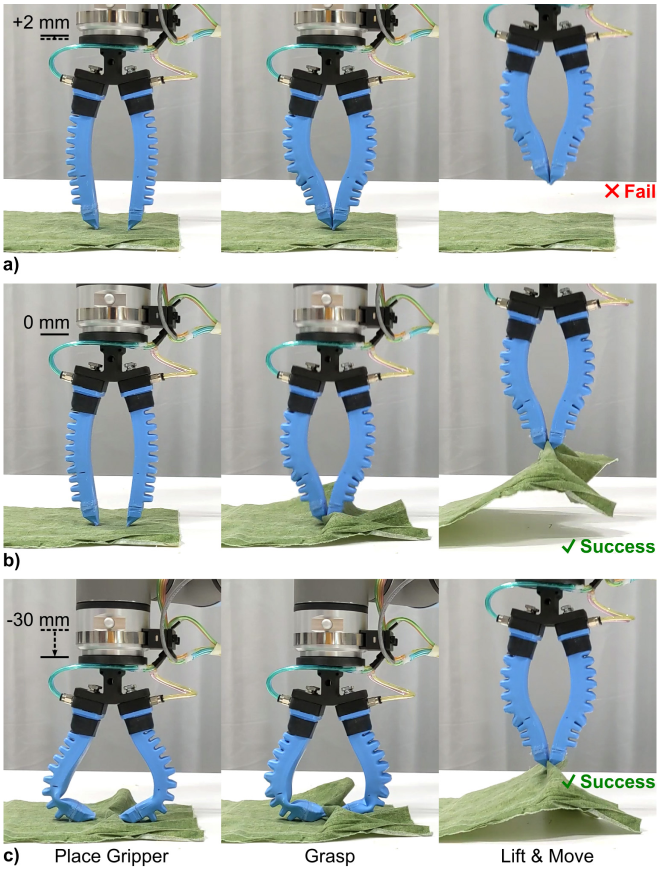

Fig. 4. For a soft gripper with 2D compliance attempting to grasp a 1 mm-thick swatch of fabric from a table, the region of allowable vertical uncertainty in the gripper's position is very large (30 mm). Example grasp sequences are shown with fingers a) 2 mm above the table, b) just pressing the table, and c) pressed 30 mm below "just-pressing".

arm's safety stop condition. Conversely, the soft gripper can handle large vertical offsets (30 mm total) with no decrease in performance, as shown in Figure 4. The soft gripper can successfully grasp the swatch between 0 mm and - 30 mm below the initial position, since the fingers can compress and bend to adapt to the vertical position offset. Additionally, this - 30 mm lower bound is limited by grasping instabilities due to insufficient stiffness out-of-plane. We would expect even larger operating ranges with a simple redesign.

B. Robustness During Non-Prehensile Manipulation

In addition to a top-down grasp, we demonstrate that vertical compliance is essential for non-prehensile manipulation (e.g., planar sliding on the tabletop surface) of thin, flexible materials. With the same 1 mm thick cotton swatch and same range of centering offsets as in the previous experiments, the grippers were commanded to press down on the swatch, then slide it perpendicular to the tabltop to a final pose. A grasp is considered successful if the swatch ends in the final pose.

We find that the vertical compliance of a soft gripper again greatly increases the range of allowable vertical uncertainty that can be handled compared to a rigid gripper (Figs. 5, 6). For the rigid gripper, successful grasps occurred only in a small window of vertical offsets: a +2 mm vertical offset leads to failure via loss of contact with the object, and an

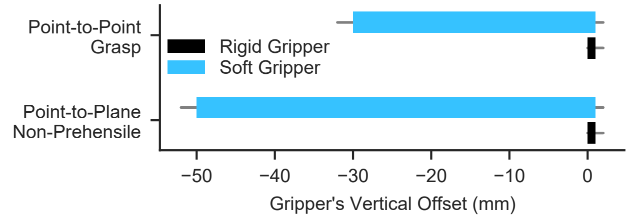

Fig. 5. The range of vertical uncertainty that each gripper can withstand is shown for both the grasping and non-prehensile manipulation tasks. The soft gripper successfully manipulates the sample under large vertical displacements, while the rigid gripper is only successful for a small range of displacements. Bars represent regions of success for $n = 1$ trial, and error bars represent uncertainty due to the resolution of positions tested.

offset of -2 mm leads to failure due to extreme forces. For the soft gripper, contact is maintained with the swatch over a wide range (50 mm) of vertical offsets.

C. Handling Snags

We investigate how both grippers compare when snagging on materials with different properties. Grasps were performed with a 0 mm vertical offset on three swatches, with relevant properties detailed in Table I. To ensure snagging behaviour is fairly compared between the two grippers, the soft gripper was operated at 100% of its pneumatic limit of 193 kPa with a grip strength of 3.17±0.01 N, and the rigid gripper's strength was matched as closely as possible (3.6±0.2 N at 15% motor torque). Due to friction limits in the rigid gripper's mechanism, 15% torque is the lowest actuation setting that still resulted in grasping motion.

Both grippers were tested in a simulated snag scenario, as shown in Figure 8. The robot was commanded to grasp one side of a swatch, then lift 5 mm and attempt to move laterally by 30 cm at a speed of $0.10\,\mathrm{m\,s^{-1}}$. The other side of the swatch was manually clamped to the edge of the table, causing a snag when the robot attempts to move the swatch. The poses of the wrist and fingertips were recorded during these tests using AprilTags [25], viewed by a world-mounted webcam at a framerate of 30 Hz, and the forces applied by the gripper to the swatch were recorded by the built-in force/torque sensor in the UR5e arm at a rate of 500 Hz. Lateral grasp displacement is calculated as the center point between the two fingers relative to the wrist, and the grasp angle is estimated as the mean of the two finger angles.

The results of these tests (Fig. 7) demonstrate that the lateral and rotational compliance of the soft gripper leads to tensile forces applied over much longer time spans than for a rigid gripper. This is due to the large lateral grasp

TABLE I

PROPERTIES OF SWATCHES USED IN SNAG EXPERIMENTS

Swatch Type	**Thickness** *(mm)*	**Young's Modulus** *(MPa)*
Elastic (spandex)	0.69 ± 0.02	0.21 ± 0.053
Woven (cotton)	0.41 ± 0.08	12.0 ± 0.16
Woven (cotton), Folded	3.03 ± 0.01	0.56 ± 0.046

Values are the mean ± standard deviation of $n = 4$ trials. Thickness is measured using ASTM standard D1777 [26] with 0.16 kPa *preload*

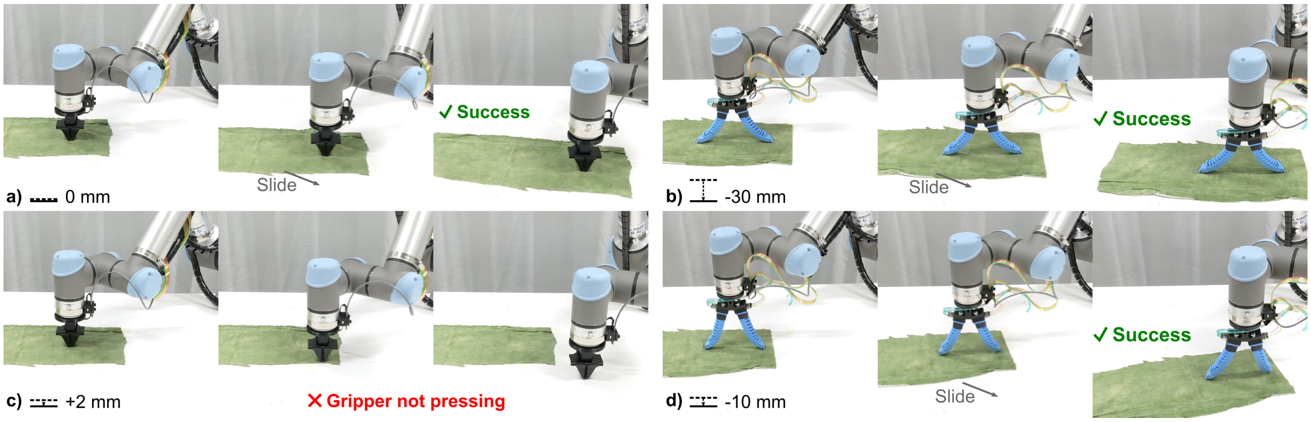

Fig. 6. Visual comparison of the rigid vs. soft gripper performing non-prehensile (extrinsic) manipulation of a piece of cloth by sliding it on a tabletop). a) The rigid gripper is successful at moving the swatch when perfectly positioned, but c) a small vertical offset of just 2 mm results in failure to contact the swatch. b,d) Conversely, the soft gripper is successful in manipulating the swatch with large vertical offsets.

displacement during a snag: For all swatches, the lateral and angular displacement of the grasp during snags was large (>30 mm, >25°) for the soft gripper, and negligible (<1 mm, <2°) for the rigid gripper. In addition, forces were applied to inextensible (woven) swatches over ~twice as long a period with the soft gripper as with the rigid gripper in both cases. The elastic swatch, however, saw forces applied over the same amount of time for both grippers ($p > 0.5$), due to that swatch's high compliance (Table I).

For context, if the arm were to manipulate the woven swatch at more realistic speeds, such as $2\,\mathrm{m\,s^{-1}}$ (20× our testing speed), the rigid gripper would take 12 ms to reach maximal snag force, which is only enough time for six force measurements to be made with our robot's force/torque wrist sensor. The soft gripper would take 25 ms, allowing for 12 measurements to be made. With a more compliant soft gripper, this time could be lengthened as needed to enable the robot to detect and react in time to prevent damage.

Our results also show that lateral and rotational compliance results in lower force thresholds before grasp failure, even when grip strength is held constant. The maximal snag force before grasp failure was consistently lower for the soft gripper for all swatches tested. The largest difference appeared for the folded swatch, where the rigid gripper applied more than 2× the lateral force of the soft gripper before failure, despite having the same nominal grip strength.

D. Task-Relevant Demonstration

To demonstrate the benefits of the planar compliance of soft grippers in a real-world task, we consider an example of table-cleaning in the restaurant industry. Robot cleaners are likely to interact with delicate objects such as wet napkins or paper towels, which could be caught underneath cutlery or crockery. In our demonstration, a damp paper towel is caught under a heavy bowl (Fig. 1). The rigid gripper tears the towel slightly during grasping due to high normal forces, then tears it badly when pulling laterally due to the large tensile force induced in the towel. By contrast, the soft gripper successfully grasps the towel even under a small vertical offset without causing damage, then passively rotates when the towel snags, releasing the grasp before any permanent damage occurs.

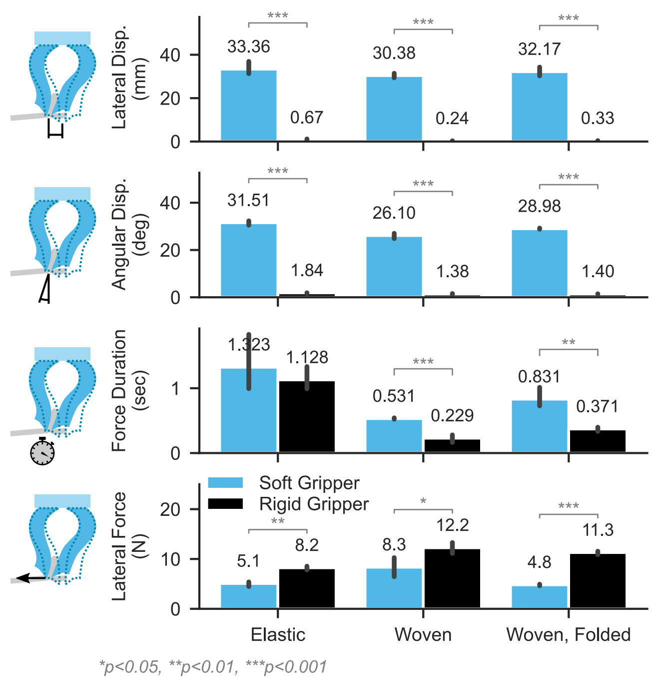

Fig. 7. The lateral and rotational compliance of the soft gripper enable it to gracefully handle snags. During a snag with both elastic and woven materials, lateral and angular grasp displacement, duration of applied lateral force, and the lateral force on the swatch are shown. Bars and errorbars represent the mean and standard deviation for $n = 3$ trials, and statistical significance is calculated using t-tests.

IV. Discussion

Our results demonstrate that the same feature (multi-dimensional compliance) that enables soft robots to gently interact with commonly-studied objects also has important benefits for handling thin, flexible objects. For both pre-hensile grasps and non-prehensile manipulation, the gripper inherently operates on or near tabletop surfaces. Vertical compliance in a gripper enables gentle, force-limited inter-

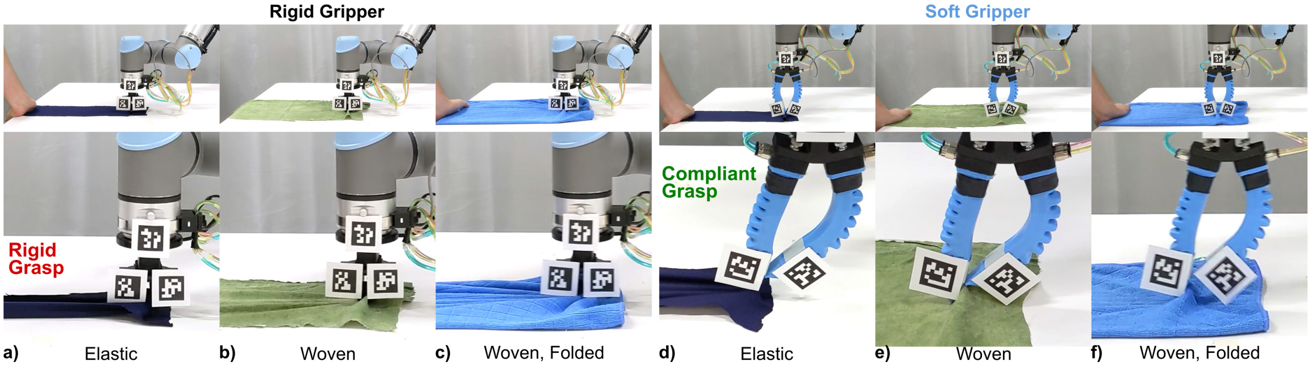

Fig. 8. Visual comparison of rigid and soft grippers in the presence of a lateral snag (one side of the fabric swatch is fixed to the table). The lateral grasp displacement as well the grasping angle during the snag are negligible for the rigid gripper, but large for the soft gripper, enabling graceful grasp failure during snags without damaging the swatch.

actions with the table, even with large vertical position error. This can be particularly useful in situations where visual perception is difficult or unreliable. In addition, once a swatch is grasped, an unexpected snag could occur, which causes tensile forces to be applied to the object by the robot. We showed that lateral and rotational compliance in the gripper serves to: 1) decrease the maximal tensile force applied, leading to passive force-limited grasps and 2) increase the time over which these forces are applied, which directly reduces the sensing bandwidth required to successfully detect snags before damage occurs in the swatch.

One key limitation of this study is the coupling between lateral and rotational compliance in our testing. Decoupling these two axes of compliance was impossible with the soft gripper used in this study due to its design. To fully explore the effects of lateral and rotational independently, one could design two more grippers modeled after the ”lateral” and ”rotational” conditions shown in Figure 2. This would illuminate the precise roles of each axis of compliance, and enable further understanding toward gripper design.

Furthermore, while only two values of compliance were tested in this study, we expect the results to apply to gripper designs with intermediate compliance as well. If the three directions of compliance could be fully decoupled and tuned independently per an application's specifications, finer-grained control over the exact forces applied to a swatch could be achieved. Through characterization of the maximal expected error in perception for a given robotic system, the vertical compliance of the gripper can be tuned to provide safe interaction with tabletop surfaces without sacrificing precision. With proper characterization of the maximum allowable tensile forces before damage occurs to a given material, the rotational and lateral compliance of the gripper could be tuned to set an upper limit on snag forces and a limit on speed such that onboard sensors can detect the snag quick enough for the robot to react. Furthermore, the interaction between vertical and lateral compliance should also be tuned taking the grasp approach angle into account.

Finally, we note that compliance is not necessarily required to be implemented at the finger level. While this is the most common implementation in the soft robotics space, a gripper with rigid fingers could utilize compliant finger pads or a highly compliant wrist to obtain the same performance benefits with respect to grasp robustness and snag resistance. However, the rigid components could still cause damage to materials during grasping or rapid motion, and the robot would also lose the benefits of finger softness when manipulating other delicate objects.

V. Conclusions

We have demonstrated that a soft robotic approach to gripper design increases a robot's ability to safely grasp and manipulate thin, flexible objects, as well as facilitating detection and recovery from unexpected snags. We discussed the critical roles that planar compliance plays in successful handling of thin materials, and quantified these effects with a hardware case study. We showed that vertical compliance enables graceful handling of vertical uncertainty as well as limiting potentially damaging forces applied to objects. We also showed that lateral and rotational compliance can prevent damage to objects during unexpected snags by decreasing the maximal tensile forces applied, and increasing the time window over which those forces are applied. Overall, we have shown that a soft robotic gripper with planar compliance can achieve all of these benefits through passive means.

These results give rise to a number of future directions in studying robotic handling of thin, flexible materials. One promising area involves using variable-stiffness actuators, where dynamic control of both vertical and lateral stiffness could enable a gripper to adapt for materials of different fragility. Another possible area of interest is the use of onboard sensors in the fingers to directly detect snags early via finger deformation. Finally, compliant grippers could enable higher success in bi-manual manipulation tasks, mitigating any potential snag forces between hands.

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