Controlling Palm-Object Interactions Via Friction for Enhanced In-Hand Manipulation

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***Abstract*—In-hand manipulation is necessary, yet challenging for robotic hands as robots begin to interact with real-world objects and environments. The intentional incorporation of an active palm can lead to improved dexterity. In this work, we demonstrate how controlling the palm-object interaction enables access to different sets of motion primitives. We first discuss how various properties of the palm affect in-hand manipulation, as well as grasping. Here, we focus on varying the friction force between the object and the palm by either changing the coefficient of friction or the normal load. We explore how these two design factors can be actively controlled to enable 5-degree-of-freedom object motion within the hand. We present *variable-friction* and *variable-preload* palms that enable on-the-fly switching between in-plane and out-of-plane manipulation modes. Additionally, we discuss their impact on grasp stability. Finally, we demonstrate how an object can be translated and pivoted within the hand by sequentially performing synchronized palm and finger actions.**

***Index Terms*—Dexterous Manipulation, in-hand manipulation, soft robot applications, soft robot materials and design.**

I. Introduction

As ROBOTS become more viable for use in the real world, dexterous manipulation emerges as an important capability for robots to achieve their goals. Many activities of daily living require "gentle dexterity", where objects are handled lightly, yet securely and nimbly, particularly when the arm is constrained (e.g., picking plates or food items from a cupboard, or loading dishes and cutlery into a dishwasher) [1]. For example, food handling tasks, such as placing delicate produce at correct positions/orientations while packing a grocery bag or unloading into the fridge, require a delicate, dexterous touch. Finally, collaborating with humans during assembly tasks while remaining safe in their proximity may involve transitioning the grasp to maneuver tools in the hand (e.g., grasping a tool from a box, then presenting it to a human with the handle exposed). For these tasks, the hand should ideally be able to grasp objects and manipulate them about all six degrees of freedom (DOFs), while minimizing damage to objects and the environment.

Substantial advances in gripper and hand design have occurred over the past four decades, which has led to the development of many robotic hands optimized for grasping. Rigid robotic hands (such as the Barrett Hand [2] and Robonaut hand [3]) have demonstrated strong and precise grasps, but require sophisticated motion planning when uncertainty exists in perception of the objects or the environment. Compliant hands and grippers (such as SDM, iHY, CLASH, RBO Hand 2) are mechanically robust to uncertainty in the environment, so they tend to perform better on a large variety of objects, however, often at the expense of strength or precision [4]–[10]. For all of these hands, the design of the palm (if one is present) is a high-friction and often compliant material which aides the fingers in securely grasping the object [2]–[8].

In addition to the passive palm designs of the aforementioned hands, many recent works have developed actuated palm structures which help improve grasp robustness. Meng, *et al.* developed a soft, telescopic palm device designed to absorb impacts with objects [11]. Jamming-based palm designs have also been employed to easily conform around objects to further secure them in a grasp with the fingers [12], [13]. The shape of the palm has also been explored, where Capsi-Morales, *et al.* used a motion-synergistic approach to design a palm that can change concavity to increase the workspace of the Pisa/IIT SoftHand [14]. Several actuated palm designs in the literature also focus on controlling the base positions of fingers rather than utilizing the palm itself as a control surface [15]–[18]. While these studies yield important results for grasping, the role of the palm changes when performing in-hand manipulation.

For in-hand manipulation, the goal is no longer to secure the object, but to control its motion relative to the hand. Most recent advances in hand design for in-hand manipulation focus on increasing finger dexterity [8], [19]–[22]. However, the palm's surface takes on new functions during in-hand manipulation: a surface on which to slide or tip the object. While some work has been done investigating the effect of palm design on in-hand manipulation [8], [23], [24], this area is still ripe for exploration. Examining the palm designs of these dexterous hands reveals a roughly flat surface for supporting objects, and

Manuscript received September 9, 2021; accepted January 3, 2022. Date of publication January 18, 2022; date of current version January 25, 2022. This letter was recommended for publication by Associate Editor Yu Zheng and Editor Hong Liu upon evaluation of the reviewers. comments. This work was supported in part by the National Science Foundation under Grant EFMA-1830901 and in part by the Space Technology Research Institutes under Grant 80NSSC19K1076 from NASA's Space Technology Research Grants Program. *(Corresponding authors: Clark Teeple.)*

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Digital Object Identifier 10.1109/LRA.2022.3143578

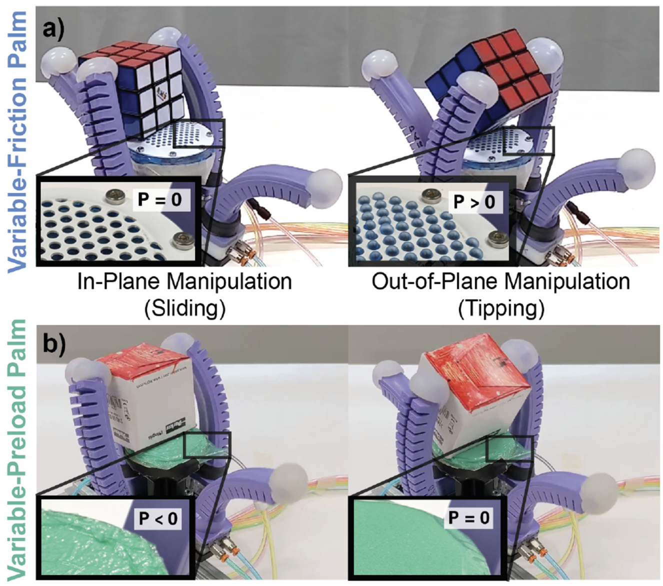

Fig. 1. Varying the amount of friction force applied to the object by the palm (by utilizing either a *variable-friction* palm or a *variable-preload* palm) enables different in-hand manipulation primitives (sliding vs. tipping). (a) The *variable-friction* palm has a soft high-friction membrane underneath a rigid low-friction porous surface. Pneumatic actuation exposes the high-friction film, increasing the coefficient of friction. (b) The *variable-preload* palm has a compliant open-cell foam housed inside a thermoplastic elastomer pouch. With the object held securely by the fingers, pneumatic actuation raises or lowers the surface, thereby modulating the normal force.

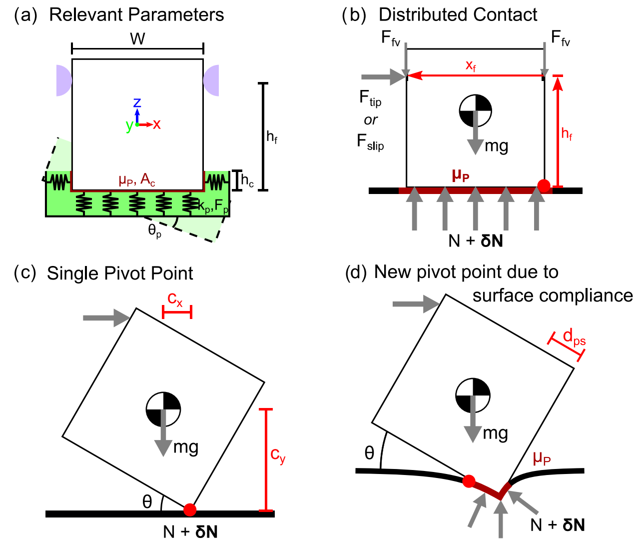

Fig. 2. (a) Schematic of physical properties to consider when designing a palm for a robotic hand. All properties affect grasping and/or in-hand manipulation performance, as detailed in Table I. Both palm designs exploit contact switching between sliding and fixed contact to control whether an object translates laterally or rotates about a pivot point. b-c) For a flat surface, the friction coefficient directly determines whether an object will tip or slip. d) For a compliant palm surface, the palm provides a new lateral surface constraint and new pivot point when the object sinks into the surface.

either a high-friction material for grasp stability and pivoting (e.g., Shadow Hand [19], BCL-26 [8], RBO Hand 3 [21], and Pagoli, *et al.* [24]) or low-friction material to enable sliding [20], [23]. Palm compliance is also a key design factor to enable gentle interaction with delicate objects [5], [8], [21].

In this work, we show that active control of friction forces between objects and the palm of a soft robotic hand can be used to enhance in-hand manipulation capabilities and improve grasp stability. Through a simple analysis, we show how two key design parameters (friction coefficient and preload) directly control an object's slipping vs. tipping behavior when finger forces are applied. We also show how mechanical compliance can be used to reduce the finger forces required to tip objects. We then demonstrate these concepts using our soft robotic hand platform by building two physical prototype palms which can actively control either the friction coefficient or normal force on the object, as shown in Fig. 1. We found that active control of both the *variable-friction* palm and the *variable-preload* palm allows the hand to translate and pivot the object given identical finger actuation, whereas a passive palm design could only achieve one of these manipulation modes. We show that the active palm designs also contribute substantially to grasp stability. Finally, we demonstrate that through sequential motion primitive operations, the active palms enable the soft hand to perform real-world manipulation tasks.

II. Grasping and In-Hand Manipulation Requirements

In this work, we identify two main capabilities that our robotic hand prototype should be capable of: 1) in-hand manipulation in the plane of the palm *and* out-of-plane, as shown in Fig. 1 and 2) robust, stable grasping. The ability to control five axes of object motion (lateral translations, lateral rotations, and rotations about the axis normal to the palm), allows the hand to move objects to any orientation through sequential primitive motions. Simultaneously, the hand must still maintain stable grasps to ensure it can withstand external forces (such as gravity or acceleration due to arm motions). Here we discuss how these goals lead to palm design requirements.

Our in-hand manipulation goal is to achieve both planar and out-of plane object motion. To achieve planar motion, the palm must act as a surface on which the fingers can slide the object, enabling x-y translations and z-rotations (as defined in Fig. 2). To achieve out-of-plane manipulation, we can utilize pivoting to rotate the object about a contact point or line on the palm without slipping (achieving rotation about x and y axes with some coupled translation). To enable both sliding and pivoting, these two competing requirements must be met either by increasing the dexterity of the hand (fingers, palm, or both), or utilizing extrinsic dexterity (such as gravitational forces, object dynamics, or environment constraints [25]). While increasing the number of controlled degrees of freedom in each finger could enable switching between planar and out-of-plane object motion[26], we show that the same effect can be achieved with a single DOF in the palm.

For strong grasping, the goal is to secure the object within the hand while resisting external forces. With compliant fingers, external forces will usually result in object motion, but finger compliance maintains the grasp even under large deformations. The failure criterion is governed by friction with some number of "virtual fingers", of which the palm can act as one or more.

TABLE I
PHYSICAL PROPERTIES OF THE PALM AND CONSIDERATIONS FOR AN ACTIVE DEGREE OF FREEDOM

Phenomenon	Physical Property	Practical Considerations for Active DOF: Pros	Cons
Surface Interactions	**Friction coefficient**	**Directly determines tipping vs. slipping behavior when palm is flat**	**Depends on pairing of objects and palm surfaces, so must consider a range of values.**
	Surface roughness	Determines friction coefficient	Can be unpredictable depending on material choice.
	Contact area	Useful if location of contact could be controlled	Difficult to reliably control for a large variety of object geometries
Local Geometric Constraints (Conformability)	Conformal depth	Surface can act as a wall	Depends on the elasticity, vertical stiffness, and object mass.
	Stiffness	Can affect the force required to tip object	Behavior depends on elasticity
	Elasticity	Determines how the depth of confirmation is affected by external loads	Mechanisms with low elasticity and low vertical stiffness may be difficult to reset
	Preload	**Palm can control the normal force on the object during grasping, thereby controlling the critical magnitude of friction forces**	**Strength of preload force must be matched to finger strength/stiffness.**
Surface Location	Position (w.r.t. fingers)	Requires only a simple linear mechanism, as shown in [11], [23]	Width of the palm must decrease as a function of height to ensure no collisions with the fingers
	Orientation	Controls the direction of the surface normal, which could be used to direct object motion	Exact effect is unpredictable for a large variety of objects.

* *Properties selected for further study are marked in* ***bold***.

The palm's contribution to grasp stability occurs at small deformations, where it helps resist moments and lateral loads initially. Thus, our goal is to build a palm that can help resist the largest forces possible before the object displaces.

Toward the goal of enabling both grasping and in-hand manipulation capabilities with a gentle touch, we explore how the palm's surface can be actively modulated for on-the-fly control of contact constraints on the object. In addition, palm compliance can enable gentle interaction with objects and make our in-hand manipulation goals easier to achieve with strength-limited fingers (as discussed below).

III. Design Parameters and Analysis

There are a variety of physical properties that could be considered when designing a palm, but some of them are more straightforward than others to control. We present a list of options along with practical considerations for controlling them with an actuated mechanism. We consider three high-level phenomena that are relevant for the design of palms: surface interactions, local geometric constraints (i.e., conformability), and surface location. Fig. 2(a) illustrates the relevant physical properties associated with each phenomenon.

To identify the most-relevant physical properties to explore, we need to consider our goal of developing a palm with one actuated degree of freedom that enables strong grasping and switching of in-hand manipulation modes. Table I details the benefits and drawbacks of each property when considering it for use as an actuated degree of freedom. Furthermore, a simple analysis of tipping vs. slipping of an object on the palm's surface illuminates two main relevant parameters, both of which are related to frictional contact with the object: the friction coefficient and preload.

A. Analysis of Tipping vs. Slipping

To understand how the friction and stiffness of the palm affect in-hand manipulation, we can look to a simple static analysis of the hand-object system at key time points. In both cases, designs that control either of these properties will exploit contact mode switching between sliding and fixed contact. Determining conditions for contact mode switching to occur has been studied extensively as an essential part of motion planing for pivoting of objects [27], [28]. The mode switching directly controls whether an object translates laterally or rotates about a pivot point when finger forces are applied. Fig. 2(b)–(d) illustrate how both parameters affect this contact mode switching behavior.

For a palm with a rigid, flat surface with friction coefficient μ_p, we analyze whether the object will tip or slip. This analysis consists of two conditions to check: the force required for the object to slip, F_{slip} (obtained by balancing forces), and the force required to tip, F_{tip} (obtained with a moment balance about the pivot point). The condition with lower force determines which motion will occur. For a palm surface orthogonal to gravity, we analyze the point at which the object just starts to slip or tip, resulting in:

$$F_{slip} = (N + \delta N)\mu_{\mathbf{p}}, \qquad N = 2F_{fv} + mg \tag{1}$$

$$F_{tip} = \frac{mgc_x + F_{fv}x_f}{h_f} \tag{2}$$

where N is the normal force from the palm, δN is an additional preload applied by the palm, F_{fv} is the vertical reaction force applied by the fingers, m is the object's mass, g is the acceleration due to gravity, c_x is the horizontal distance from the pivot point to the center of mass, h_f is the vertical height of the fingers with respect to the palm, and x_f is the horizontal distance between the finger and the pivot. For any given object (constant m, c_x,) and hand (constant h_f, x_f), the friction coefficient μ_p and preload δN are the only controllable parameters.

Our initial design goal is to actively control the palm's surface to select whether objects slide or pivot within the hand for a wide range of objects. Examining (2) shows that for a given hand (constant h_f and x_f), the object mass and size determines F_{tip}, while (1) indicates that only the mass affects F_{slip}. To maximize the potential for pivoting over a large range of object masses, mass distributions, and sizes using the two controllable parameters, we must maximize F_{slip} by maximizing μ_p or δN. Conversely, to maximize the potential for objects to slip, we must minimize F_{slip} by minimizing μ_p or δN. Thus, only a binary mechanism is required, where the difference between high and low states is maximized.

For a palm with a compliant surface, the previous tip/slip analysis applies for objects that are lightweight compared to the palm's stiffness. Such low-mass objects sink into the palm a negligible amount under their own weight at rest. However, when objects are in the tipping mode and the palm's stiffness is suitably matched to the object's mass, the palm's compliance allows the object to sink into it. This provides a new surface constraint and shifts the pivot point toward the center of mass (as shown in Fig. 2(c)–(d)), which plays an interesting role: decreasing the overall finger force required to tip the object. To analyze this effect, we can perform a static moment balance for an object of width W pivoting on a soft surface at angle θ such that the pivot point shifts toward the center of mass by a distance d_{ps}. This results in (3):

$$\begin{aligned} F_{tip} &= mgX_c/Y_f, \\ X_c &= c_x cos\theta - c_y sin\theta - d_{ps} cos\theta, \text{ and} \\ Y_f &= W sin\theta + h_f cos\theta - d_{ps} sin\theta. \end{aligned} \tag{3}$$

where c_y is the vertical distance from the pivot point to the center of mass. The pivot shift distance (d_{ps}) is related to the stiffness of the palm, the mass of the object, the contact area, and the pivot angle. However, for this analysis we assume it is a small constant distance that can be prescribed for simplicity. Thus, we show that a compliant palm decreases the finger force required to tip an object via a small shift in the pivot point. For a typical square object with a pivot adjustment distance (d_{ps}) of $10\,\%$ of the object's width, the required finger force to tip the object decreases by $20\,\%$ compared to if the palm were rigid ($d_{ps} = 0$), which could be extremely beneficial for hands with limited finger strength.

B. Final Palm Designs

We developed two pneumatically-driven palm designs, with each design exploiting one of the two critical design parameters, as shown in Fig. 3. The *variable-friction* palm is based on the mechanism in [29] to actively control the friction coefficient of the palm's surface, and a compliant, *variable-preload* palm is based on elastic, compressible foam. The principles of operation of both designs are shown in Fig. 3.

Our *variable-friction* palm controls the friction coefficient of the palm's surface via a high-friction membrane that inflates out of holes in a low-friction rigid frame. At rest, the membrane (Ecoflex 00-50, Smooth-On) is well-below the palm's surface, so objects can only make contact with the low-friction polystyrene top layer (1/16" th., McMaster-Carr). As the membrane inflates, it pushes through small holes in the top layer, creating a distributed surface with a high friction coefficient. By controlling the pneumatic pressure, we can control the effective friction coefficient of the palm's surface, as shown in Fig. 3(a).

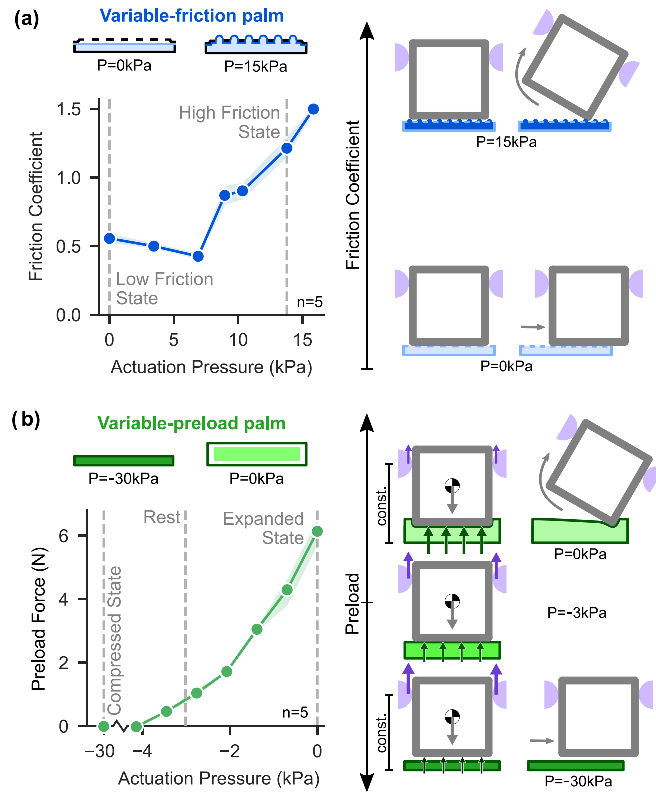

Fig. 3. The two pneumatically-driven palm designs can be used to control friction forces on the object. a) The *variable-friction* palm uses a positive air pressure signal to control the friction coefficient, μ_p between the palm and object. b) The *variable-preload* palm uses a negative air pressure signal after grasping to control the normal force on the object (applying a preload, δN), which changes the load distribution between the palm and the fingers. Controlling the tip/slip condition for the largest range of objects is achieved by switching between two extreme states for both palm mechanisms.

To measure the friction coefficient, a cardboard box (60g, 60 mm cube) is placed on the palm, then pulled laterally at $0.1\,\mathrm{mm/s}$ via a string connected to an Instron uniaxial testing machine. The maximum force sustained prior to slip is divided by the object's mass to calculate the friction coefficient. Interestingly, for the *variable-friction* palm in the "low-friction" regime (where the elastomer film does not yet protrude from the top layer), slight increases in pressure result in a bowed palm surface. This reduces the contact area between the object and palm, resulting in a lower measured coefficient of friction. We note that the specific values of the friction coefficient will vary based upon the object and palm, but the results presented in Fig. 3(a) are representative of a typical object. For the *variable-friction* palm, the friction coefficient changes by roughly $2\times$, between $0.55{\pm}0.03$ and $1.2{\pm}0.06$.

Our second design, the *variable-preload* palm, can modulate the normal force on objects after they are grasped via inflation or deflation of a foam-filled pouch. The operating principle is similar to existing vacuum-driven, foam-based soft actuators [30], [31]. A cylinder of highly-compliant open cell foam is sealed inside a pouch made of a low-friction thermoplastic elastomer film (Stretchlon 200, Airtech Intl.). At its "zero-preload" state, the pouch is placed under a small negative air pressure

($-3\,\text{kPa}$) to partially compress the foam. During a grasp, the fingers hold the object in place against the palm, and the palm's air pressure can then be modulated up or down to relax (expand) or further compress the foam, as shown in Fig. 3(b). This small change in the position of the palm's surface controls the palm's preload on the object by increasing or decreasing the normal force between the palm and object. To measure the preload, the palm was first retracted by applying -4.1kPa, then the actuation pressure was raised in 0.7 kPa increments and the resulting force was measured by the Instron machine. Across this range of pressures, the (blocked) preload force varies from $1.2\pm0.03\,\text{N}$ and $6.0\pm0.2\,\text{N}$.

IV. Results

To evaluate the performance of the two palm designs during grasping and in-hand manipulation, we performed a series of simple tests and measurements using our existing soft, dexterous hand platform [20]. This hand consists of four radially-oriented fingers, each with two orthogonal degrees of freedom. In prior work, this hand was capable of only planar in-hand manipulation, but could utilize a telescoping palm mechanism to control the object's position in the axis normal to the palm [23]. However, this hand was still incapable of rotating an object about its lateral axes, and its grasp stability was relatively low for most objects.

In this study, we replace the original palm with our new, friction-controlled palms. Using the air pressure controller setup from [20], the fingers and palm are commanded using air pressure trajectories to control grasping and lateral motions, and palm actuation states. In all experiments, the hand is operated open-loop with no external vision system or on-board sensing in the fingers or palm.

A. In-Hand Manipulation

To evaluate the effectiveness of the two palm mechanisms to control object motion, the hand was commanded to grasp an object, set the palm's actuation state, then shift the grasp location while the object's resulting motion was observed, as shown in Fig. 4. Objects of rectangular and circular cross-section were tested: a 3D-printed box ($76\,\text{g}$, $50\,\text{mm}\times50\,\text{mm}\times75\,\text{mm}$), and a plastic jar ($43\,\text{g}$, $100\,\text{mm}\times100\,\text{mm}$). After grasping the object, the grasp is translated in the x-axis, and rotated about the z-axis, and the resulting object motion is collected by inspection.

Observing the motion of the object undergoing the same finger actuations, both palm mechanisms can directly control the sliding vs. tipping behavior of objects in the hand. For the *variable-friction* palm, the low-friction state produces lateral translation of the object when the grasp is translated laterally, while the high-friction state results in pivoting (or rolling) about the axis orthogonal to finger motion. For the *variable-preload* palm, a negative preload (where the palm retracts to reduce the normal force on the object) produces lateral object translations when the grasp is moved laterally, and a positive preload results in pivoting. Rotation about the z-axis results in z-axis rotations for both actuation states of both palms.

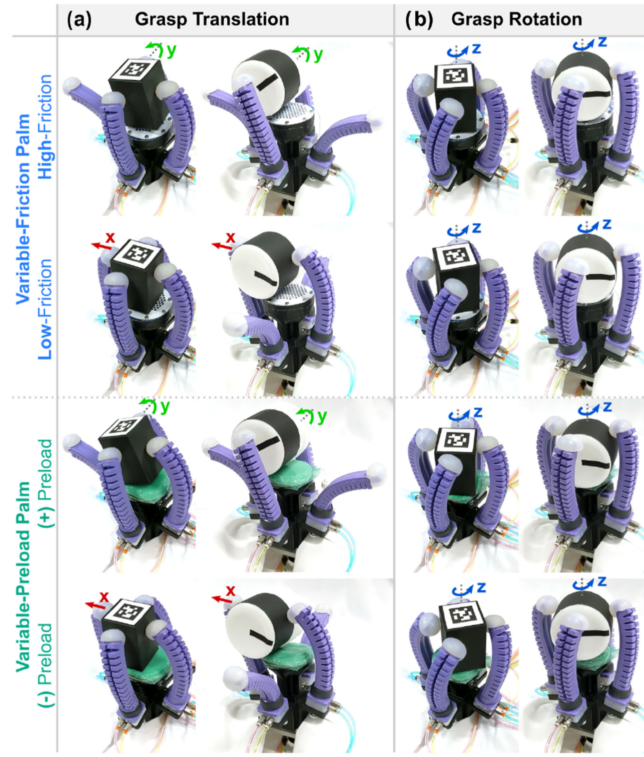

Fig. 4. The actuation of our two palm mechanisms allows the hand to control whether objects slide or tip when finger forces are applied,and thus the direction of object motion. a) As the grasp is translated in the x-direction, both palm designs control whether the object pivots or rolls about the y-axis, or slides in the x-direction. Due to the hand's symmetry, the same capabilities exist for grasp translations in the y-direction. b) Grasp rotations about the z-axis result in object rotations, but the resulting angle depends on the palm's actuation state (high-friction and + preload states result in lower range of motion). Results are collected via visual inspection.

Looking at the behavior as a whole, we see that modifying the palm's frictional characteristics with the object (either through the friction coefficient, or the magnitude of normal forces) enables switching between sliding or pivoting/rolling. If the palm is implemented as a single, passive design, the hand only has access to one of these manipulation modes (chosen at design-time). Thus, an actuated palm design, such as the two we present in this work, provides run-time control of in-hand manipulation modes, expanding the dexterity of the hand via only one degree of freedom, as shown in Fig. 4.

An added advantage of the *variable-preload* palm is that the compliance of the foam reduces the tipping force required by the fingers to rotate the object out-of-plane. This is especially important when trying to manipulate heavier objects with low finger forces, or when trying to keep forces low during manipulation of delicate objects. We demonstrate this by trying to tip a heavy object using the *variable-preload* palm. When the palm has a positive pre-load, the fingers can easily tip the object on the compliantly conforming palm. When the palm has a negative pre-load, our soft fingers (which can apply a maximum force of 2N) are not strong enough to tip the same object, as demonstrated in the supplementary video. This demonstrates the importance of compliance in a palm for in-hand-manipulation tasks that require gentle dexterity.

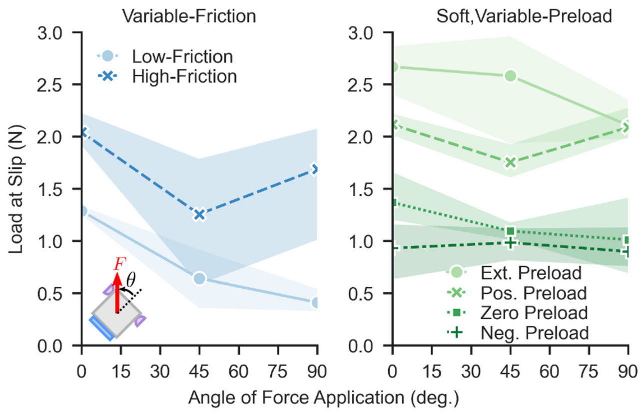

Fig. 5. The "initial grasp stability" is displayed for each actuation mode of each palm design (mean±1 standard deviation of $n = 3$ trials). We can see that for the *variable-friction* palm, the high-friction state has consistently higher grasp stability ($\sim 2\times$) compared to the low-friction state. Additionally, for the *variable-preload* palm, the grasp stability increases as a function of the preload, and an external preload on the object results in a ($\sim 2.5\times$) increase in stability compared to resting on the surface.

B. Grasp Stability

The effect of the palm on grasp stability is most directly seen in the initial grasp stability, when the object is secured in a grasp. The initial grasp stability is related to the external load (applied to the object) when the object first slips from its initial pose. To get a simple estimate of how the palm contributes the initial grasp stability, we measured the initial slipping force as a function of the angle at which force is applied. These tests were conducted per the procedure detailed in [20]. The object (a $60\,\mathrm{mm}\times 60\,\mathrm{mm}\times 60\,\mathrm{mm}$ cardboard box, as first seen in [20]) is mounted in the jaws of an Instron universal testing machine with a 2 kN load cell, and hand is mounted to a fixture where its orientation relative to the object is controlled. We then applied a constant extension ramp of $1\,\mathrm{mm/s}$ and measured the resulting force.

Fig. 5 shows the grasp stability for both palm designs as a function of the actuation mode and force application angle. We can see that for the *variable-friction* palm, the high-friction state yields consistently higher grasp stability ($\sim 2\times$ at best) compared to the low-friction state. For the *variable-preload* palm, the preload on the object has a similar effect on stability, where a negative preload leads to lower stability compared to zero preload, and positive preload leads to approximately $2\times$ higher grasp stability compared to zero preload. In addition, when the object is pressed into the palm before grasping by an external force, the hand achieves a further increase in grasp stability ($\sim 2.5\times$) compared to zero preload. Looking at the results overall, we see that both palms can modulate their grasp stability as a function of actuation, but the compliant construction of the *variable-preload* palm also allows it to make use of external preload forces if they are available.

C. Manipulation Tasks from Sequential Motion Primitives

By chaining together in-hand manipulation motion primitives discussed previously, objects can be translated and rotated to any desired orientation. Fig. 6 illustrates the sequence of palm and finger actuation required to perform a full 90° out-of-plane rotation of a box. Briefly, this requires the object to be slid so that the edge of rotation is shifted close to the center of the finger workspace, followed by a tipping motion. We leverage the palm's abilities to change friction or preload against the fingers to trigger whether slipping or tipping occurs with equivalent finger actuation. The objects used in this demonstration are a Rubik's Cube, a cardboard box ($60\,\mathrm{g}$, $60\,\mathrm{mm}\times 60\,\mathrm{mm}\ \times 60\,\mathrm{mm}$), and a cylindrical plastic jar ($43\,\mathrm{g}$, $100\,\mathrm{mm}\times 100\,\mathrm{mm}$). Videos of these demonstrations can be found in the supplementary video.

To further demonstrate the utility of the grasping and in-hand manipulation capabilities afforded by control of the palm's friction, we show a food preparation task. The goal of the task is to present a sandwich bun with the sliced side out such that a worker can fill it with sandwich toppings, then place it on a plate. The successful task is shown in the supplementary video. To accomplish this task, a UR5e robot arm (Universal Robots) is outfitted with our soft hand and the *variable-friction* palm. The arm grasps the bun, engages its high-friction state for maximal grasp stability, then flips the hand upside down, allowing the bun to rest on the palm's surface. Next, the hand utilizes the sequence of primitive motions detailed above to slide and pivot the bun 90° placing a the pre-sliced side of the bread upward. The bun is loaded with toppings by a worker, then pivoted 90° to place the top of the bun facing the palm. Finally, the completed sandwich is placed on a plate, right side up.

V. Discussion

Our results demonstrate that active control of the friction force between the palm of a robotic hand and the object it interacts with has a direct effect on in-hand manipulation modes and grasp stability. In this section, we discuss how these results can inform future hand designs, what additional factors (beyond isolated palm design) should be considered, and how these results could be generalized.

Active control of the friction coefficient or preload between the palm and object can play a large role in determining the direction of in-hand object motion (sliding vs. pivoting) when finger forces are applied. This is accomplished by controlling which constraints on object motion the palm provides through contact with the object. This is especially relevant for robotic hands with limited finger dexterity since, as demonstrated here, a single actuated DOF in the palm can be used instead of added dexterity in each finger. In the future, the addition of one translational degree of freedom in the palm (normal to the surface) would enable the hand presented here to achieve full 6-DOF control of the object, potentially unlocking more complex in-hand manipulation capabilities.

Controlling the frictional characteristics of the palm also allows for control of grasp stability, but the upper bound is limited for both palm designs. For controlling the friction coefficient, the grasp stability improvements are limited by the available material choice (elastomers tend to have the highest coefficients already). Through control of the preload, the gains in grasp stability are limited by the strength (and friction coefficient) of

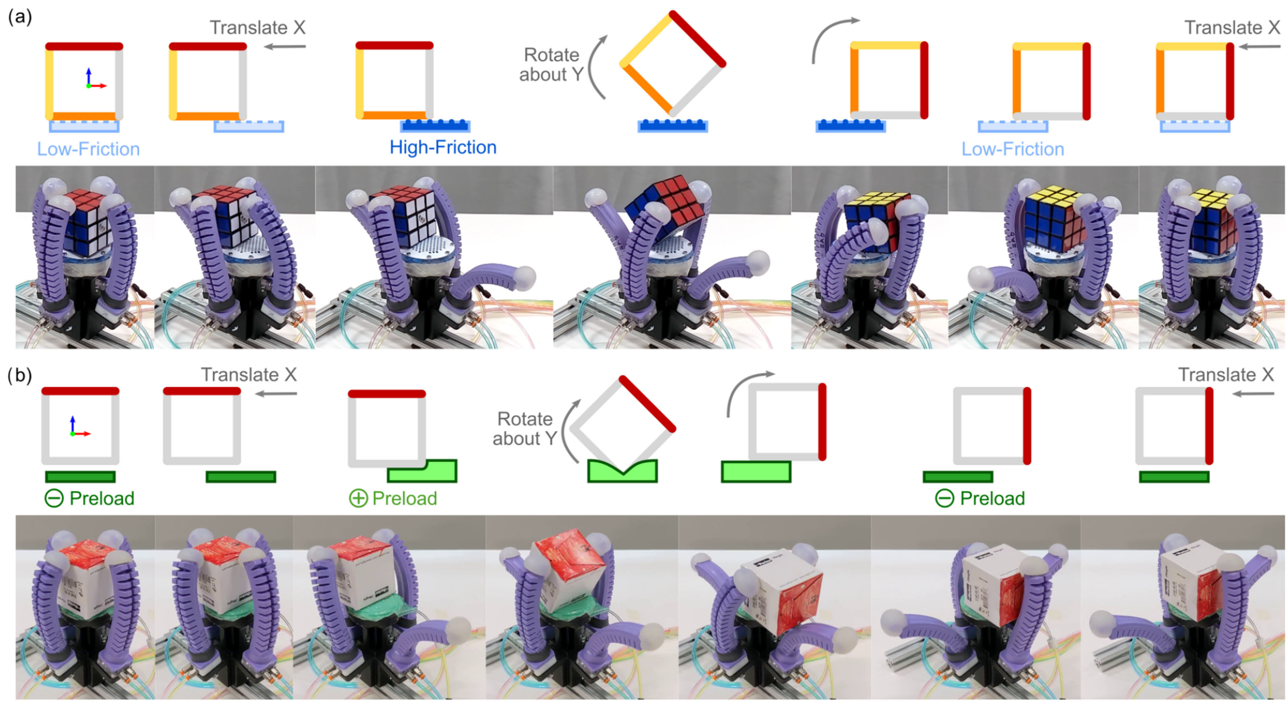

Fig. 6. Controlling the palm's surface enables the soft hand to perform arbitrary pose shifts on an object through combinations of sliding and tipping, using either the variable-friction palm (a) or the variable-preload palm (b).

the fingers, since the palm presses the object against the fingers when applying positive preload. Thus, the range of acceptable preload forces must be matched to the finger strengths.

In addition to the two main design parameters, we showed that building a palm with a compliant surface has several real, measurable benefits for grasping and in-hand manipulation. A compliant palm can substantially decrease the finger forces required to tip heavier objects, as analyzed and demonstrated in this study. We also showed that palm compliance can be used to take advantage of external preloads (i.e., via the environment) before grasping an object with the fingers to increase grasp stability. Both of these benefits are especially useful for soft robotic hands whose fingers are often weak compared to the weight of many common household objects.

In addition to the palm's design, a large factor in the design process should be the target set of objects. For example, for a desired set of objects, the palm's materials and actuation modes must be chosen such that the range of friction coefficients and/or preloads between the palm and the object set are different enough to enable the desired contact mode switching behavior. Furthermore, while we used rectangular and circular objects in this study to demonstrate the palm's impact on in-hand manipulation, we expect our analysis and results to remain pertinent even for objects with more interesting geometries. However, the precise motion of objects in the hand will be affected by the object's center-of-mass and position of the fingers on the object.

Finally, further exploring the effect of palm-object interactions on in-hand manipulation in a more quantitative manner could yield insights into the complexity of these interactions. For example, measuring the manipulability of the object in the hand as a function of the palm's applied constraints could indicate which physical mechanisms dominate. This could also shed more light into the coupling of the hand's performance to its pose and directions of external forces or constraints. Future palm designs could then be developed based on a more bottom-up approach.

VI. Conclusion

In this paper, we demonstrated how control of the friction force between an object and the palm of a soft robotic hand dictates slipping and tipping behaviors, and thus in-plane and out-of-plane motions, during manipulation. Through a theoretical analysis, we showed that tip vs. slip behavior can be determined by the friction coefficient and the preload of the object on the palm, given the same object and finger force. Furthermore, we show in this analysis that a compliant palm lowers the force required to tip an object, a note of particular interest for soft robotic hands that are often underpowered. With these design concepts in mind, we fabricated two pneumatically-driven palms, a *variable-friction* and a *variable-preload* palm. We experimentally verified that by actuating the palms, the same finger motion can result in either sliding or tipping, generating both in-plane and out-of-plane motion primitives. Additionally, we showed that the grasp stability can also be varied via the actuation state of the palms. Finally, through a sequence of grasping and in-hand manipulation motion primitives, we demonstrated that controlling the palm-object interaction enables a robot to stably grasp an object, then re-orient it in 5-DOF.

The area of palm design for robotic hands has great potential for future innovations. Most immediately, we are interested in a more in-depth study of the palm design concepts presented in this paper as they pertain to real application tasks. For example, choosing the range of friction coefficients or preloads could enable control of in-hand manipulation of a wider range of objects or tasks. Continuous control of the actuation space (rather than binary) and spatially modulating the friction forces could enable a finer-grained approach to controlling contact interactions. We are also interested in further exploring how both compliance and plasticity of the palm can benefit grasping and in-hand manipulation. Looking further into the future, this work could be expanded upon to achieve greater control of objects within the hand. Combining the two palm designs presented in this paper with a variable height mechanism would enable the hand to control finger placement on the object, potentially enabling 6-DOF control of the object's pose. With careful engineering, active palm surfaces could be a gateway to highly-dexterous in-hand manipulation with relatively simple hands.

Acknowledgment

The authors would like to thank Daniel Bruder, Moritz Graule, Justin Werfel, Andy Cohen, and Kaitlyn Becker for valuable discussions during development. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the funding organizations.

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