An Adaptive Three-Fingered Prismatic Gripper With Passive Rotational Joints

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***Abstract*—In this letter, we present the design of an underactuated three-fingered robotic hand and evaluate its performance. The hand utilizes radially symmetric, prismatically actuated fingers controlled by a single actuator. Each finger consists of a single joint finger connected to the prismatic joint via a passive rotational joint perpendicular to the palm. The rotational joints allow the fingers to passively switch between spherical and cylindrical grasps while the finger joint allows the fingers to wrap about the grasped object. We compare the performance of this design to that of a concentric gripper with cylindrical fingers and two other underactuated hand designs using the YCB grasping benchmark. This evaluation shows that the three finger prismatic hand performs well especially when equipped with the single joint fingers in comparison to other designs.**

***Index Terms*—Grasping, grippers and other end-effectors, mechanism design of manipulators, multifingered hands.**

I. Introduction

The complexity of existing robotic hands varies greatly, ranging from simple single degree of freedom (DOF) parallel jaw grippers to high DOF anthropomorphic hands such as the Shadow and DLR hands [1], [2]. Between these extremes are many hand designs that utilize one or a few actuators and some combination of fully actuated, passive, and coupled degrees of freedom [3]–[13]. By driving multiple joints with a single actuator through an intelligently designed transmission mechanism, underactuated hands are both simple to control and capable of grasping more complex irregular objects than fully actuated, single degree of freedom end effectors. However, these hands are still tailored to particular grasps or classes of objects and not truly general purpose grippers.

Although underactuated hands such as the SDM or Barrett Hands are capable of grasping a wide range of objects, particularly when using an enveloping grasp, the success of these grasps is often dependent on a grasping strategy for the particular object and hand [3], [14]. For example, it is often desirable to align the hand with the principal axis of the object to maximize the likelihood of achieving a successful grasp and the grasp's ability to resist perturbations [15]. In this letter we present the design of a novel underactuated hand inspired by this strategy.

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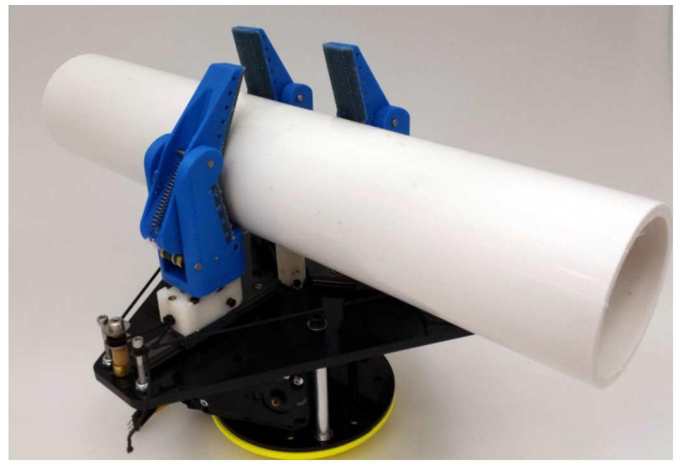

Fig. 1. Example of the Model S hand with single joint fingers grasping a cylindrical object. The finger pads are parallel to the object surface and the fingers wrap about the object demonstrating the adaptive behavior of the passive joints and caging capabilities of the single joint fingers.

Instead of having to align the hand with the principal axis of the object, the hand is designed to passively adapt to the principal axis of the object for most initial configurations using the same grasping strategy. This hand, named the Model S, is shown in Fig. 1. It consists of three coupled prismatic joints, aligned symmetrically at 120 degrees from each other, driven by a single actuator. A single joint finger is mounted to each of these active joints by a passive, sprung rotational joint and the flexion of each finger is driven via the same tendon that actuates the prismatic joint. When the hand grasps an object, the initial contacts cause the fingers to rotate until each finger pad is tangent to the local object curvature at contact. Continued actuation causes the fingers to flex, wrapping about the object. These two adaptive degrees of freedom increase contact area which in turn increases the maximum shear forces that contacts can support and reduces the chance that the object will be dropped [16].

Although we were unable to find evidence of hands with similar overall kinematics in the literature, individual aspects of this design can be observed in other robotic hands and industrial fixturing apparati. Common fixturing apparati like three jaw chucks and industrial grippers such as the three finger concentric grippers made by Schunk consist of three prismatic fingers driven by a common actuator [17]. Hanafusa and Asada describe a radially symmetric three finger hand with finger tips consisting of rollers to minimize tangential friction [11]. Theobald et al. describe how they built "spring suspended fingers" for the Talon gripper that allow "each of the five fingers to rotate about its own base while constrained

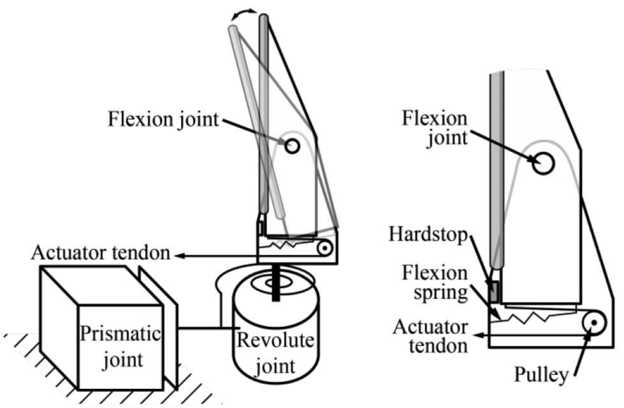

Fig. 2. Diagram of the finger kinematics (left) and detailed view of the flexion mechanism (right). Each finger consists of an actuated prismatic joint, an unactuated revolute joint with return spring, and a finger with an actuated flexion joint. The extension of the flexion joint is limited by a mechanical hard stop and achieved via a spring.

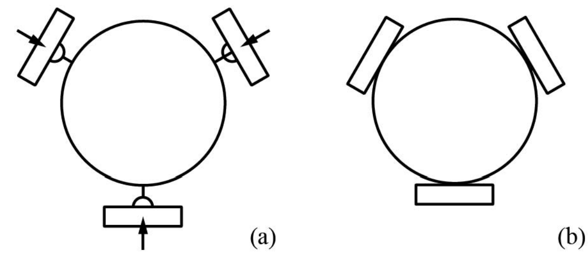

Fig. 3. Diagrams of the hand performing a spherical grasp when viewed from above. When grasping an object that presents a circular cross-section to the hand, it behaves similarly to a simple concentric gripper and the fingers (shown here as simple rectangles) move inwards (a) until they all make contact with the object (b), securely grasping the object.

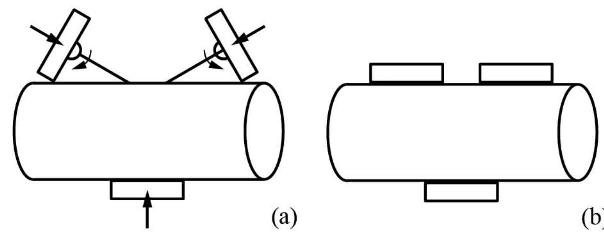

Fig. 4. Diagrams of the hand performing a cylindrical grasp when viewed from above. When grasping objects that do not present a circular cross section, the passive revolute degrees of freedom allows the fingers to conform to the object geometry. When the fingers make contact (a), they rotate until all three finger pads are tangent to the object. This results in a secure grasp (b) that maximizes the finger pad contact with the object.

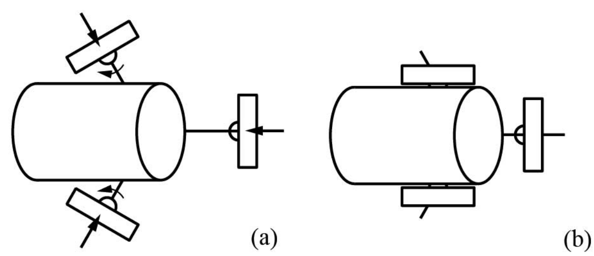

Fig. 5. Diagrams of the hand performing a two fingered grasp. When the object only contacts two fingers, the passive degree of freedom at the base of each finger allows the fingers to conform to the object geometry as shown here. When the fingers make contact (a), they rotate until both fingers are tangent to the object. This results in a secure grasp (b) pinching the object between the two fingers.

by torsional springs" [18]. The Barrett Hand, Robotiq adaptive robot gripper, Festo MultiChoiceGripper, and iRobot-Harvard-Yale Hands all feature active adduction and abduction of two fingers, allowing these hands to actively switch between a cylindrical and spherical grasp so that an enveloping grasp can be used in more situations [6], [10], [19], [20]. Lastly the MLab hand features a similar radially symmetric three fingered design but utilizes revolute joint fingers and relies on finger geometry and elastic elements between the common actuator and each finger to achieve passive between the finger adaptability to conform to object shapes [21].

In this letter we begin by presenting the design of the new gripper. We describe the kinematics of the fingers and how they reconfigure when grasping as well as the design of the finger and placement of the finger pad relative to the rotational joint axis. Next we explain how the hand is fabricated and describe how it is evaluated. Lastly we present the results from the evaluation and discuss its performance and limitations as well as future improvements we plan to make to the design.

II. Design

The hand design we present here consists of three identical prismatically actuated fingers radially arranged about the hand's center. In comparison to simple concentric grippers such as those made by Schunk [17], this design extends the capabilities of this type of hand by adding two additional rotational degree of freedom per finger. The serial kinematics of each finger (shown in Fig. 2) consists of an actuated prismatic joint extending radially outward from the hand's center in the plane of the palm followed by a rotational joint whose axis is normal to the palm. The rotational joint is not actuated but includes a weak return spring. This spring centers the finger so that the surface of the finger pad is perpendicular to the prismatic joint axis before the finger makes contact. Distal to this joint is the finger, consisting of a flat, compliant finger pad and a single actuated flexion joint. The extension of the finger pad is achieved via a return spring and limited by a mechanical hard stop while the flexion of this joint is actuated by the same tendon used to actuate the prismatic joint, as shown in Fig. 2. When combined these degrees of freedom cause the finger to translates until it makes contact, then rotate until it is tangent at the contact point, and lastly flex, to wrap about the object, resulting in a secure grasp.

A. Adaptive Behavior

When grasping a cylindrical object from above, as shown in Fig. 3, the fingers pads are already tangent to the object and the hand's behavior is very similar to a concentric gripper. However, when grasping objects that do not present a circular cross section to the hand, the additional finger degrees of freedom causes the hand to passively adapt to the objects geometry as shown diagrammatically in Figs. 4 and 5. For example,

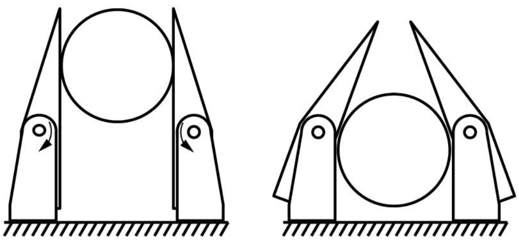

Fig. 6. Diagram showing the side view of the flexor behavior of the fingers. When performing either a spherical or cylindrical grasp, once the fingers make contact, the actuated flexion degree of freedom causes the fingers to wrap about the object (left), resulting in a more secure grasp as shown (right).

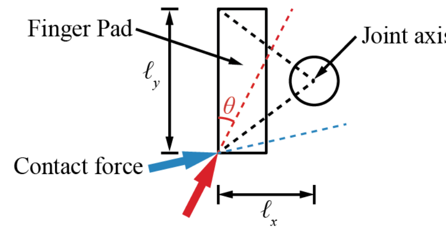

Fig 7. Diagram of relationship between finger pad and passive revolute joint axis when viewed from above the hand. Two example contact forces are shown in red and blue with their respective lines of action drawn in with the same colored dashed line. If the line of action of the contact force passes behind the joint axis (for example the blue force vector) it will cause the finger to rotate until the finger pad surface makes contact with the object. However, if it passes in front of the axis (for example the red force vector), the finger pad will rotate away from the object, resulting undesirable contact on the side of the finger.

if the principal axis of the object is parallel to the palm of the hand (such as the example grasp of a cylinder shown in Fig. 4) or when the geometry is irregular, when closing the hand, the edges of the finger pads contact the object first and the adaptive behavior of the passive revolute joint causes each finger to rotate until it is tangent at the contact as shown in Fig. 4. The adaptability of the revolute joint also helps the hand securely grasp objects using only two fingers as shown in Fig. 5. In this situation the passive rotation of the finger bases allows the two fingers that contact the object to reconfigure until they are tangent to the contact points, pinching the object between the fingers. Regardless of if only two or all three fingers contact the object, this adaptive behavior maximizes the contact area with an irregular object and thereby increases the expected strength of the grasp.

In addition to the revolute degree of freedom, the fingers also possess a flexion degree of freedom as shown in Fig. 6. When grasped objects make contact at the finger tip, the individual fingers behave like rigid links and this joint does not reconfigure. However for more proximal contacts, once the fingers are tangent to the object, the flexion degree of freedom allows the fingers to wrap about the object as shown in Fig. 6. This adaptive behavior helps the hand cage the object, thereby further increasing the strength of the grasp.

B. Kinematic Design

To ensure the desired adaptive behavior of the passive rotational joint, proper positioning of the finger pad surface relative to the joint axis is critical. As shown in Fig. 4(a), when the edge of the finger pad contacts an object, the contact force should cause the finger to rotate about the passive joint until the finger pad makes full contact with the object. However, as shown in Fig. 7, this reconfiguration behavior is dependent on the direction of the contact force in relation to the joint axis: if the line of action of the contact force passes behind the joint axis, the contact will cause the finger to rotate until the finger pad is tangent to the object as desired but if it passes in front of the joint axis, the finger will rotate in the opposite direction until contact is made on the side of the finger. Placing the finger pad in front of the joint axis (as shown in Fig. 7) is desirable since it allows the hand to grasp smaller objects but decreases the range of allowable initial contacts that will result in the desired moment and reconfiguration behavior. This limitation may be addressed by using a remote center of compliance instead of the rotational joint to position the joint axis well in front of the finger pad while keeping the mechanical components behind the finger pad but this has not been investigated yet due to the added mechanical complexity it would entail.

Instead we find the maximum distance that the finger pad can be placed in front of the joint axis (ℓ_x) while ensuring that the line of action of the contact force will pass behind the revolute joint axis for a particular finger pad width (ℓ_y) and worst case contact condition. We can express the maximum allowable distance of the joint axis behind the finger pad as follows: $\ell_x < 0.5\ \ell_y\ \tan(\theta)$ where θ is the angle between the line of action of the contact force that passes through the join axis and the surface of the finger pad. For a cylindrical object in the ideal case shown in Fig. 4(a), $\theta = \pi/6$ so: $\ell_x < 0.5\ \ell_y \tan(\pi/6)$ for the finger to reconfigure in the desired direction. However to ensure that the finger will consistently rotate in the desired direction even for more irregular objects the revolute joint axis must be placed closer to or behind the joint axis. To ensure consistent adaptive behavior of the hand in all cases, we positioned the finger pad 1.5 mm behind the joint axis

The adaptive behavior of the flexure joint is determined by the positioning of the flexure joint axis relative to the tendon attachment and contact location as well as the stiffness of the flexure return springs. The relationship of these components can be analyzed by considering the sum of moments about the joint axis of all of the forces applied to the finger as follows: $\sum M = F_c\ell_c - F_t\ell_t - k_r\Delta\theta = 0$ where F_c is the contact force, ℓ_c is the perpendicular distance from the joint to the contact force, F_t is the tendon force, ℓ_t is the perpendicular distance from the joint to the tendon force, k_r is the spring stiffness, and $\Delta\theta$ is the angular displacement of the return spring from rest. From this expression it is clear that for small spring stiffnesses, if $(\ell_c > \ell_t)$, the finger will hyperextend until its motion is limited by the extension hard stop and if $(\ell_c < \ell_t)$, the finger will flex inward, wrapping about the object. Based on these expected behaviors, we positioned the flexion joint axis 2 mm proximally from the center of the finger, ensuring that the finger will wrap about objects when grasping except when the object makes contact at the finger tip. In this special case, the finger pads remain parallel and the object is pinched between the finger tips.

C. Fabrication

Based upon these design decisions, we have built a prototype of the hand using methods derived from the Yale OpenHand [22]. The body of the hand is made from laser cut 3 mm delrin and 3D-printed ABS components (printed on a Fortus 250mc). The fingers are also 3D-printed and the finger pads are cast using Smooth-On VytaFlex 30 urethane rubber. The finger-pad of the one link finger is 15 mm wide and 77 mm tall. A steel extension spring (McMaster Carr 9654K955) is used as return springs for the flexure joints in each finger. This spring is preloaded to resist finger flexion until the finger contacts and object. The prismatic and rotational joints are constructed using off-the-shelf linear and rotational bearings (Igus TK-04-09 and Dynaroll SRW188ZZ A5). Elastic bands are used as return springs on both joints (1/4” Medium stiffness orthodontic elastics and 0.05 in diameter shock cord respectively). The stiffnesses of these springs were selected to overcome the stiction of the revolute and prismatic joint’s respective bearings. A Robotis Dynamixel MX-64 servo operating at 12 V is used to actuate all three fingers directly via 100-lb test Spectra fishing line tendons.

In order to evaluate the advantages of this design we also fabricated a simple version of the hand that duplicates the capabilities of a commercial concentric gripper equipped with compliant cylindrical fingers rigidly attached to the prismatic joints. We chose to use cylindrical fingers for this comparison because their geometry ensures that the object will be tangent to the finger surface regardless of the objects position in the hand. Each cylindrical finger is 25 mm in diameter, 82 mm long and is made out of Smooth-On VytaFlex 30 urethane rubber cast about a 0.25 inch diameter aluminum rod.

III. Gripper Evaluation

In order to quantify the grasping capabilities of the single joint finger design of on this hand and compare it to the performance of both the simple cylindrical fingers and to other hand designs, we have evaluated the hand according to the gripper assessment protocol described by Calli et al [23]. We also evaluated the grasp strength of both finger designs based on a pull out force test modified from the National Institute of Standards and Technology (NIST) slip resistance metric [24]. Lastly, we measured the size, weight, and grasp force of the hand and reported these specifications along with other relevant hand parameters. We then compare these results to the other hands that have been evaluated using this protocol.

The gripper assessment protocol involves the human operator planning and the robot arm executing preplanned grasps of the objects listed in Table I including a set of spheres ranging in size from 17.4 mm to 145 mm, a set of washers ranging in size from 9.8 mm to 50.8 mm, a credit card, and a number of tools and other common objects. For each object, the operator begins by finding a grasp strategy that consistently grasps the object at the target position. The hand is then scored based on its ability to pick up each object from a smooth tabletop using the preplanned grasp from the target position as well as when the object has been moved by 10 mm in x, y, or z direction without changing the grasp trajectory. The success of each grasp at each point is then scored out of 4 possible points. One point each is awarded if the object is picked up, if it does not move in the grasp, if it remains in the grasp when the hand is rotated 90° about both the x and y axes, both of which are parallel to the palm of the hand, and if it does not shift after these rotations have been performed.

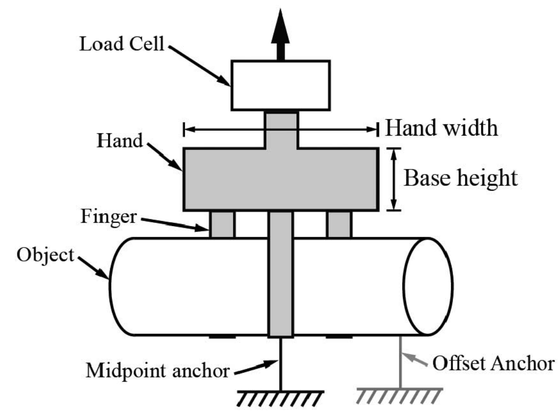

Fig. 8. Diagram of grasp strength test. The hand is suspended from the load cell of a universal testing machine and grasps a representative object that is centered in the grasp. The object is anchored to the base of the testing machine either from its midpoint or a point offset 100 mm to one side (shown in light grey) while the load cell is moved upwards at 25 mm/minute.

The assessment procedure for articulated objects (a plastic chain and length of rope) differs slightly: for this test, the object is piled in the center of the workspace and grasped. The grasp is considered a success if the articulated object does not touch the table top after the hand is moved up 15 cm. This procedure is repeated 20 times and each successful grasp is awarded 0.5 points. The subscores for each class of objects (spheres, washers, tools, and articulated objects) as well as the total score are computed by summing all of the points for that set of objects and are reported in Table I for each finger design.

To measure the grasp strength of the different finger designs we evaluated object pull out strength of the finger designs using a protocol modified from the preliminary NIST slip resistance test [24]. Unlike in the NIST test, where a cylindrical object is pulled sidewise out of the grasp, effectively measuring the friction forces exerted by the grasp, we measure the force required to pull the object out of the grasp cage perpendicular to the palm. To test the grip strength, the hand is suspended from a 1 kN load cell of a universal testing machine (Instron model 5542) and grasps a cylindrical object using a constant motor torque as shown in Fig. 8. The object is centered in the hand and positioned in a configuration equivalent to how it would be picked up off of a tabletop. The object is also anchored to the base of the testing machine using a spectra tendon. The load applied to the hand is then measured while the hand is moved upward at 25 mm/minute. The test is terminated when the object is pulled out of the grasp and the grasp strength reported here is the recorded peak load prior to major reconfiguration of the hand (where contact is lost with one finger or the object makes contact with the back of the hand). For each test, the motor torque of the Dynamixel MX-64 servo is

TABLE I
SCORING TABLE FOR GRIPPER ASSESSMENT

	Object	Size (mm)	Single joint finger				Cylindrical Finger			
			Target	10 mm x	10 mm y	10 mm z	Target	10 mm x	10 mm y	10 mm z
Round Objects	Soccer Ball	⌀145	4	4	4	4	4	4	4	4
	Softball	⌀95	4	4	4	4	4	4	4	4
	Tennis ball	⌀65	4	4	4	4	4	4	4	4
	Racquetball	⌀55.5	4	4	4	4	4	4	4	4
	Golf ball	⌀42.7	4	4	4	4	4	4	4	4
	Marble (XL)	⌀35.4	4	4	4	4	4	4	4	4
	Marble (L)	⌀24.1	4	4	4	4	4	4	4	4
	Marble (M)	⌀22.2	4	4	4	4	4	4	4	4
	Marble (S)	⌀17.4	4	4	4	4	4	4	4	4
Flat Objects	Washer 1	⌀50.8x3.7	4	4	4	NA	4	4	4	NA
	Washer 2	⌀37.3x2.7	4	4	4	NA	4	4	4	NA
	Washer 3	⌀31.6x1.2	4	4	4	NA	4	1	3	NA
	Washer 4	⌀25.3x1.7	4	4	4	NA	4	4	4	NA
	Washer 5	⌀18.8x1.9	4	4	4	NA	4	4	4	NA
	Washer 6	⌀12.9x1.3	4	4	4	NA	4	4	3	NA
	Washer 7	⌀9.8x1.3	4	4	4	NA	4	4	4	NA
	Credit card	85.5x53.9x0.75	4	4	4	NA	4	4	4	NA
Tools	Pen	Sharpie	4	4	4	4	4	4	4	0
	Scissors	Wescot 3.5" blade	4	4	4	4	4	4	4	4
	Hammer	13 oz stanley	4	4	3	4	4	4	4	4
	Screwdriver	stanley philips	4	4	4	4	4	4	4	4
	Peg XL	Nylon spring clamp	4	4	4	4	4	4	4	4
	Peg L	Nylon spring clamp	4	4	4	4	4	4	4	4
	Peg M	Nylon spring clamp	4	4	4	4	4	4	4	4
	Peg S	Nylon spring clamp	4	4	4	4	4	4	4	0
Articulated	Chain	1168 long	9.5	NA	NA	NA	7	NA	NA	NA
	Rope	3530 long	10	NA	NA	NA	10	NA	NA	NA
Score	Round objects:		144/144				144/144			
	Flat objects:		96/96				91/96			
	Tools:		127/128				120/128			
	Articulated:		19.5/20				17/20			
	Total:		386.5/388				372/388			

set using the Dynamixel wizard software. The resulting total tendon force was measured for both a cold and hot motor and peaked at between 67 and 81 N and decayed to between 53 and 59 N over 3 minutes.

To test the hands capabilities as a function of object size and center of mass location, two different anchoring conditions and object sizes were tested for each finger design. Based on the NIST protocol we used 12 inch segments of 1 inch (1.315 inch OD) and 2 inch (2.375 inch OD) schedule 40 PVC pipe as the test objects. The pipes were anchored to the base of the universal testing machine via a spectra tendon threaded through a small hole in the pipe wall. During the tests the objects were anchored either from their midpoints resulting in a pull straight down on the hand or from a point 100 mm axially from their centers, testing the hands ability to resist a moment or grasp an object far from its center of mass. Each of these test conditions was repeated five times and the mean and standard deviations are reported.

Lastly, the specifications of the hand are measured in the following ways. The base height is measured from the bottom of the hand to the base of the finger, excluding the coupling used to quickly attach and detach it from the robot arm as shown in Fig. 8. The base width is reported as the diameter of the circle that circumscribes the base plate. The grip force is measured by grasping a load cell (Transducer techniques MLP-25) as diagramed in Fig. 4 and commanding a fully closed position to the actuator. This procedure is repeated for all object orientation in the hand and the range of grip forces achieve are reported.

IV. RESULTS AND DISCUSSION

Table I shows the results from the grippers assessment and Table II shows the results from the grasp strength tests for the Model S hand with both finger designs. Fig. 9 shows examples of the hand equipped with both the cylindrical and single link fingers grasping various objects used in the gripper assessment. Additional examples of the hand grasping various objects can be seen in the video submission that accompanies this letter. Lastly, Table III shows how the performance of the Models S hand compares to the Model T and Model T42 hands that have also been evaluated using the gripper assessment benchmark [23].

TABLE II
HAND PULL OUT STRENGTH

Finger Design	1 in tube, centered		1 in tube, offset		2 in tube, centered		2 in tube, offset	
	mean	deviation	mean	deviation	mean	deviation	mean	Deviation
Model S – cylindrical finger	18.3 N	3.1 N	3.9 N	0.29 N	21.9 N	0.94 N	8.9 N	1.2 N
Model S – single joint fingers	58.1 N	6.2 N	27.8 N	2.4 N	93.9 N	7.9 N	37.7 N	2.2 N

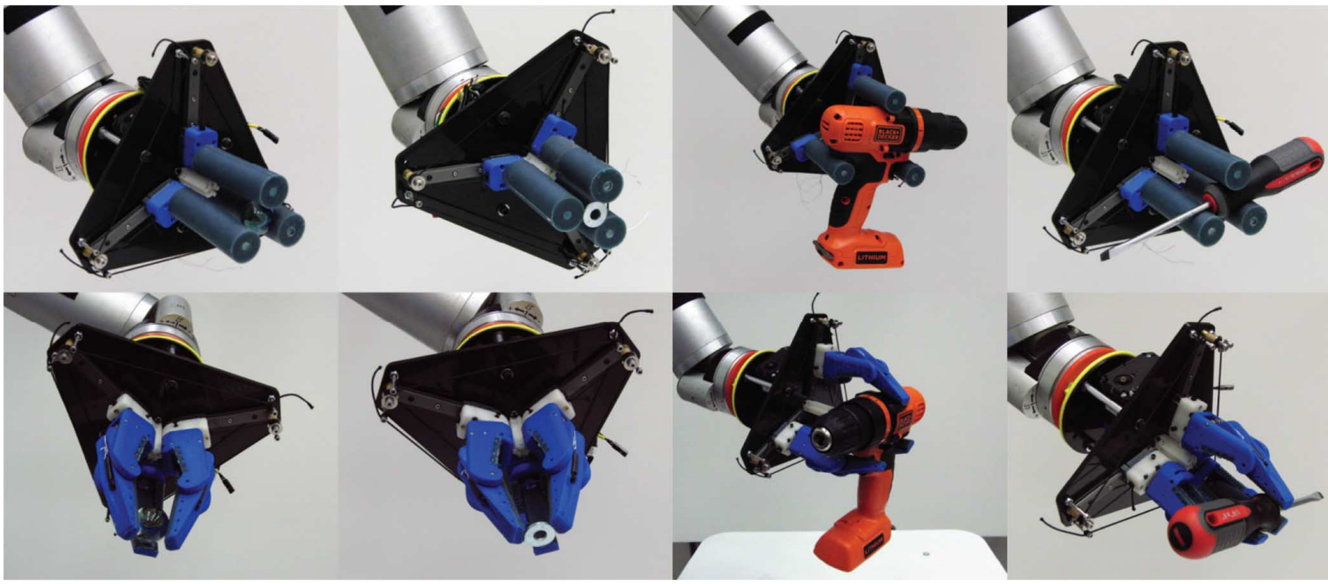

Fig. 9. Examples of the hand grasping various objects from the object set. The top row shows example grasps with the cylindrical fingers while the bottom row shows examples of the single joint fingers. The first column shows the hand grasping the large marble, the second shows the hand grasping the 18.8 mm washer, the third shows it grasping a drill and the fourth, a screw driver. Although both finger designs are capable of grasping all of the tested objects from the original position, as can be seen here, the single joint fingers wrap about larger objects like the marble, drill, and screw driver, increasing the strength of the grasp. Demonstrations of these and other successful grasps can also be seen in the video submission that accompanies this letter.

TABLE III
GRASPER COMPARISON

Hand	# Fingers	# Actuators	Base Height (mm)	Base Width (mm)	Weight (g)	Grip Force (N)	Hand Score
Model S – cylindrical finger	3	1	90	211.6	746	40-45	372/388
Model S – single joint fingers	3	1	90	211.6	766	40-60	386.5/388
Yale Model T	4	1	95	100	490	11.5±1.2	122/388
Yale Model T42	2	2	55-80	90-105	400	9.6±0.25	356/388

A. *Gripper Performance*

As can be seen from the subscores for each class of objects in Table I and for each finger design, this hand performs very well overall on the grasping benchmark. The single joint fingers scored 386.5 points out of a possible 388 points. In comparison, the simple version of the hand equipped with the cylindrical fingers scored 372 points while the Model T and Model T42 hands scored 122 and 356 points respectively.

The Model S hand equipped with the single joint fingers can grasp objects from 5 mm to 130 mm in diameter using a spherical grasp like the one diagramed in Fig. 3. The minimum grasp diameter is the result of the corners of the finger tips contacting each other as they close and the maximum diameter is restricted by the travel limit of the prismatic joints. Therefore, when equipped with these fingers, the hand is capable of grasping all of the spherical objects except the soccer ball using a spherical grasp. Although the soccer ball is larger than the maximum open diameter of the hand, it can be grasped by jamming the fingers into the object and closing them, locally deforming the object and achieving a successful grasp.

The hand also performs well when grasping the thin/flat objects, successfully grasping all of the washers and the credit card. The finger tip geometry and the flexion degree of freedom in the fingers both contribute to its success grasping these objects. The squared off finger tip ensures that when it is pressed against a surface, the thin object contacts the front of the pad and does not slip under the finger tip. The flexion degree of freedom also contributes to the hands performance when grasping thin objects by adding compliant in the direction normal to the palm. This added compliance allows the hand to be firmly press against the tabletop to compensate for any errors in z position without damaging the hand. Ensuring that the fingertips make contact with the surface in turn prevents thin objects like the washers from sliding under the finger tips. This compensation for errors in z that the finger compliance affords is also beneficial when grasping small objects like the pen and small clamp when large errors in z position are present. When grasping the round objects, tools, and articulated objects, the flexion degree of freedom also allows the fingers to wrap about these objects, increasing the strength of the resulting grasps. However in most of these grasps, the object contacts the fingers near their distal end and does not make contact with the palm or bases of the fingers. In most cases this type of grasp is sufficient but when grasping heavy objects like the hammer it allows the object to shift from the initial grasp when it is picked up. In contrast, when these objects are manually positioning in the hand so that they make contact with both the base of the finger and the finger pad this undesired object reconfiguration didn't occur. Although contact forces on the object should cause grasped objects to reconfigure towards these posed configurations, this behavior was not observed due to the friction of the finger pads.

Like the single joint fingers, the cylindrical fingers can grasp a range of objects using a spherical grasp. This range is limited by the fingers contacting each other and by the travel limits of the prismatic actuators, resulting in a lower and upper limit of 4 and 115 mm in diameter. Also, like the single joint fingers, compliant objects that are larger than the maximum grasp diameter such as the soccer ball can be successfully grasped by jamming the fingers into the object.

Although the hand equipped with the cylindrical fingers performs well in comparison to the Model T and Model T42 hands, it doesn't perform as well as the single joint finger version of the hand. Specifically it is unable to grasp the number 3 and number 6 washers from some locations and the pen and small clamp when they have been displaced in z. These failures can be attributed to the lack of finger compliance in the direction normal to the palm of the hand inherent in the cylindrical finger design. Any position error in this direction results either in a hard collision with the ground that can damage the hand or in a gap between the fingertip and the ground that causes grasps of thin objects to fail. For example, the cylindrical fingers can't grasp the pen and small peg when they are displaced downward 1 cm since these objects are less than 1 cm thick. This limitation is also present when picking up the thin washers, requiring careful initial positioning of the hand and even failing completely in some cases such as when washer 3 is offset in x and y. These shortcomings of the cylindrical fingers show some of the benefits of the single joint design.

B. Grasp Strength

Although the two different finger designs exhibited similar performance on the grasp benchmark, their grasp strengths as measured by the pull out tests differ significantly as can be seen in Table II. In all test conditions, the maximum pull out force recorded for the single joint fingers is more than three times greater than the measured pull out force for the same condition with the cylindrical fingers. This result demonstrates that even though the two finger designs performed similarly on the object benchmark, the wrap grasp of the hand with the more complex single joint fingers results in much stronger grasps as would be expected; unlike the cylindrical fingers that rely purely on friction to prevent the object from shifting, the single joint fingers wrap around the object, caging it. Also, although the pull out force of the Model T and Model T42 hands were not measured, based on their significantly lower grasp forces, we expect that they would not perform as well as the single joint fingers on this metric. However because these two hands are designed to grasp objects using a wrap grasp, they may perform better than the cylindrical fingers which rely entirely on contact friction in this test. Lastly, because these two hands are actuated differently from the prismatic hand, effectively changing the transmission ratio between the motor and fingers, comparing their performance on this test is difficult.

C. Benchmarking

Table III compares the specifications and performance of this hand with both the cylindrical and single joint fingers to other underactuated hands that we had access to that have been evaluated using the same protocol [22], [23]. This shows that all three hands are physically similar in size and weight (although the Model S is somewhat larger and heavier). Both the Model T and Model T42 have similar grasp forces of ≈ 10 Nwhile the Model S is capable of producing grasp forces between 40 and 60 N (depending on the trial) using the same actuator as the Model T. This difference in grasp force is due to how the fingers in both hands are actuated: in the Model T and Model T42 hands, the tendon force exerts a moment about the base of the finger while in the Model S it exerts a force parallel to the prismatic joint.

These hands' scores on the gripper assessment protocol also vary significantly. The Model S performs significantly better than both the Model T and Model T42 when grasping this set of objects, scoring 265.5 points better than the Model T and 30.5 better than the model T42 on the benchmark when equipped with the single joint fingers. The Model S scored better than the Model T42 primarily because of its ability to pick up large objects like the soccer ball, very small objects like the smallest washer, and heavy objects such as the hammer and drill. It also distinguished itself when picking up the articulated objects, scoring 7.5 more points than the Model T42 when picking up the chain. All of these objects are extreme examples from their respective categories, representing the largest, smallest, and heaviest objects in each group. Although it is difficult to draw definitive conclusions from this relatively small set of objects, the Model S' superior performance on these tasks shows the design's robust and general grasping capabilities.

V. Future Work

While the hand was capable of grasping almost all of the objects we tested with fixed actuation of all three fingers, the addition of an adaptive coupling between the prismatic joints may improve the hand's adaptability. This adaptive coupling may be implemented using pulleys or a whippletree to actuate all three fingers with equal force (instead of displacement as currently implemented). However this coupling may prove problematic when grasping irregular objects that results in a net force imbalance on the object due to the contact forces applied by the two adjacent fingers on one side of the object in comparison to the force applied by a single finger on the other side of the object. This force imbalance would result in the object being pushed sideways in the grasp until one of the prismatic joints reached a travel limit. However, this behavior may be limited somewhat by restricting the travel of the differential mechanism, resulting in a hand that can better adapt to irregularities in object shape while also holding objects near the center of the hand.

Another approach to increasing the between-finger adaptability of the hand would be to add compliant elements in series with the tendons actuating each finger. This configuration allows greater adaptability than the fixed coupling currently used but would not result in severely off center grasps that we expect with an unconstrained differential mechanism.

The hand's performance may also be improved through improvements to the passive rotational joint and finger design. Specifically, by replacing the rotational joint with a remote center of compliance, we can greatly improve the adaptive behavior of the finger by positioning the joint axis far in front of the finger pad while maintaining a small minimum grasp size. Similarly, more complex finger designs such as the continuum fingers produced by Festo AG may increase the grasping performance of the hand in some situations.

Although we have only studied the three fingered version of this hand design, implementations with more fingers are feasible and may also be beneficial in some situations. In particular, when grasping large objects, additional fingers may allow the hand to better constrain the object, especially if the fingers are actuated in an adaptive manner. However, increasing the number of fingers decreases the maximum distance between adjacent fingers for a given prismatic joint limit. Therefore, this change would further limit the maximum size of object that could be grasped using a cylindrical grasp since the object must pass between adjacent fingers of the hand as shown in Fig. 4. Similarly, increasing the number of fingers will increase the minimum size of object that can be grasped since the minimum grasp size is limited by the finger's colliding with each other. Therefore we believe that additional fingers will only be beneficial on hands designed for specific tasks that involving grasping objects that do not approach the upper or lower object size limits for the hand.

VI. Conclusion

In this letter we presented the design and evaluation of a novel three fingered hand that combines prismatic and revolute joint underactuated fingers with passive revolute joints. We described the kinematics of this hand including the prismatic and rotary underactuated finger and passive revolute joints and the desired passive adaptive behaviors they enabled. We then summarized the gripper assessment protocol used to evaluate the hand and compare it to other grippers. These results show that this design is capable of robustly grasping the set of objects identified by the grasping benchmark protocol including spherical objects, thin objects, and more irregularly-shaped objects. The grasp strength tests also show how the addition of the flexion degree of freedom to the fingers greatly improves the robustness of the grasp in comparison to a simple concentric gripper. Lastly we discussed potential improvements to the hand including alternative finger actuation schemes, and the benefits and limitations of adding fingers to the hand.

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