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A Novel Nonlinear Compliant Link on Simple Grippers

Zhiwei Zhang¹, Alberto Rodriguez² and Matthew T. Mason³

Abstract—This paper presents a novel nonlinear compliant link. It has two major properties: bi-directionality and stiffening compliance. Bi-directionality means it can be stretched and compressed, and is realized by antagonistic arrangement of an extension spring and a compression spring. Stiffening compliance means it becomes stiffer as it is stretched, and is realized by asymmetric geometry. The links are parts of Simple Hand. Because Simple Hand gives limited space for links, current iteration of links is not obviously nonlinear. However, nonlinearity should be more obvious if links are designed for larger grippers.

I. INTRODUCTION

Compliance is common and important in human manipulation. Soft muscles and tendons give human hands the ability to adjust passively to target objects. Moreover, these soft tissues absorb shocks when one hammers a nail or catches a flying frisbee, protecting the body. In addition to passive ways, humans use active compliance, employing neural mechanisms in control [1] [2].

Similarly, in robotics there are two primary ways of producing compliance: a passive compliance using internal mechanical structures, or an active compliance using software control algorithm [3]. Compliant behavior has been incorporated in robotic hand designs, like the Utah/MIT hand [4], the iHY hand [5], and the ARM-H hand [6]. Dollar and Howe [7] surveyed 20 different designs of compliant and underactuated hands. Researchers also explored passive compliance between finger and contact. Cutkosky and Kao [8] derived stiffness matrix given by contact compliance and finger deformation. Shapiro [9] etc. introduced a comprehensive model for the nonlinear force-displacement relationship at a frictional contact. Active compliance were discussed in various control strategies in robotic hands; one example is impedance control in DLR-Hand [10].

Just as with humans, including compliance in robotic hand is beneficial, in that robotic hands are able to adapt to shape of target objects, and are able to protect themselves and environment from unpredicted collisions.

A novel topic about compliance in robotics is varying compliance. This idea stems from human-robot interaction, where robots have to be strong enough to fulfill tasks, but be gentle to avoid harming humans [11] [12]. A variable stiffness actuator (VSA) offers such a variable stiffness.

VSA-II [11] adopts an antagonistic idea, where two motors actuate a link via an elastic transmission. The transmission is a 4-bar mechanism attached with an ordinary torsion spring. Combination of the 4-bar linkage and torsion spring results in a nonlinear spring. DLR FSJ [13] uses a floating spring, which couples two specially shaped cams. Between the cams are two rollers. Rotary displacement of rollers gives stiffness, which can be altered by rotary pretension of one cam. In [14], a variable stiffness joint uses leaf springs to generate compliance, and uses two actuators to change compliance via a four-bar linkage. SJM-III [15] consists of an inclined link, a slider with rollers and linear springs. Nonlinear stiffness is achieved by designing the shape of the inclined link. It has high stiffness below a preset threshold torque and low stiffness above the threshold. A major difference of this design from the former three is that its stiffness is not varied actively, but passively with its contacts.

This paper is about the development of a bi-directional stiffening compliant link. With an antagonistic arrangement of two springs, the link can be both compressed and stretched. In addition to this, as it is being stretched, the link's stiffness increases. The link is part of latest version of Simple Hand, which aims at building a simple gripper capable of general-purpose autonomous manipulation. This special design of compliant link is supposed to give Simple Hand a increased potential compared to its earlier model [16].

The rest of this paper is arranged as follows. Section II talks about our motivation of designing such a compliant link, provides design idea, and derives mathematical model of the link. Section III gives its mechanical realization. Section IV gives experimental results to validate effectiveness and repeatability, followed by discussion.

II. DESIGN PHILOSOPHY

A. Motivation

Motivation of this bi-directional and stiffening property comes from our ideas of designing Simple Hand to fully explore its functionality. We wish it can do three different tasks while grasping. At first, Simple Hand approaches the target until one finger touches the target. In this period, its fingers act as tactile sensors, and we refer to this as *antenna mode*. Then, grasp choice may or may not be changed according to knowledge of the target with respect to the robotic hand. Its transmission ensures that it can adapt to the shape of the target. We call this *object-centric mode*. Then, normal forces between fingers and target increase until adequate amount of forces are achieved to grasp the target. We call this *hand-centric mode*. This idea calls for

¹Zhiwei Zhang is with Department of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, PA, USA zhiweiz@andrew.cmu.edu

²Alberto Rodriguez is with the Department of Mechanical Engineering, Massachusetts Institute of Technology, Boston, MA, USA albertor@mit.edu

³Matthew T. Mason is with the Robotics Institute, Carnegie Mellon University, Pittsburgh, PA, USA matt.mason@cs.cmu.edu

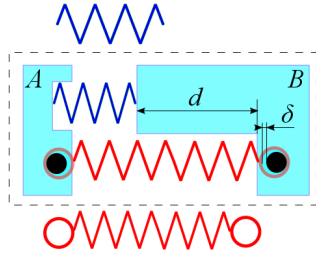


Fig. 1: Illustration of antagonistic arrangement of springs. Illustration in dashed box demonstrates antagonistic arrangement of springs. A and B are two link parts, which move horizontally. Blue spring indicates compression spring, upper one being of its original length. Red spring indicates extension spring with hooks, lower one being of its original length. Black circles indicate extension spring fixers. There exists pretension in this illustration: when no force is exerted, compression spring is compressed, and extension spring is extended.

three requirements: antenna mode requires a bi-directional low stiffness to sense contacts or collisions effectively; object-centric mode requires compliance; hand-centric mode requires a high stiffness. All these three requirements result in a bi-directional and increasing stiffness.

From perspective of mechanical engineering, nonlinear compliance of robotic hands, whether is introduced intentionally or unintentionally, comes from all components: finger, tendon, joint, timing belt, *etc.* Different from VSAs mentioned in Section I, compliance in Simple Hand is from links. The design of Simple Hand is such that links are ideal positions to add compliance: compliant links need less space; they are easier to manufacture; their shape can be altered without changing other parts greatly. Moreover, link compliance changes passively as a function of link length, eliminating the necessity of stiffness-change motors as in VSAs. Link length can be computed with data from its joint encoder and the motor encoder, which further gives information on link force. These are reasons for putting compliance on links.

B. Antagonistic Arrangement of Springs

Antagonistic arrangement of a compression spring and an extension spring gives bi-directional compliance, as shown in Fig. 1. Two ends of extension spring are attached with part A and B respectively, and left end of compression spring is attached to A , leaving right end floating. This attachment is due to the fact that extension springs usually come with hooks, but compression springs without. When the link is stretched, the extension spring allows the link to extend; when the link is compressed, the compression spring allows the link to shrink.

Length d in Fig. 1 is a variable that defines combined behavior of the antagonistic arrangement. There are three cases (Fig. 2): (a) the neutral case, where d is just the value d_0 that there are no forces exert on springs at free length; (b) the pretension case, where $d > d_0$, the compression spring

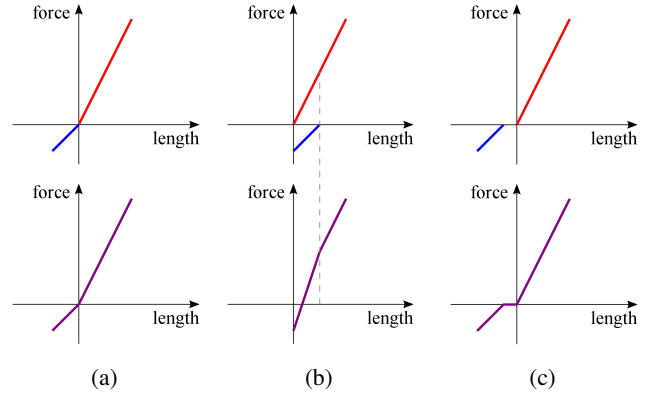


Fig. 2: Three cases of antagonistic arrangement: (a) neutral case, (b) pretension case, and (c) wiggling case. For each column, upper figure shows force profile for extension spring (in red) and compression spring (in blue). Combined profiles of two springs are shown in lower figures, and are dyed in purple.

is compressed and the extension spring is extended (also illustrated in Fig. 1). At overlapping, combined stiffness is sum of all spring stiffness: $\sum_i |k_i|$; (c) the wiggling case, where $d < d_0$, there is a gap (Fig. 2c), leaving a zero-force region. Here, analysis in (a) and (c) assumes that the extension spring will not be compressed. This assumption holds true if the installation gap (δ in Fig. 1) between hook and pin is utilized to give extension spring free moving space during compression, and if let compression displace $d_{compress} < \delta$.

These three arrangements each have shortcomings; we have to make a tradeoff. The neutral case requires accurate manufacturing, which contradicts with fundamental ideas behind Simple Hand Project of easy manufacturing and low cost. In pretension case, stiffness in coupled region increases as a result of parallel springs. As the coupled region is also where we want a low stiffness, this arrangement contradicts with our intention. Moreover, the coupling makes it impossible to design the compression and the extension spring individually. However, if the coupled region is small and if the increased stiffness is not big compared to one without a compression spring, this design is still acceptable. The wiggling case has a zero-force region. Although this zero-force region makes the link extremely sensitive to small force disturbance, false signals will be generated when the hand accelerates, which may be misinterpreted as collisions. Another drawback of the neutral and wiggling case is their small compression distance. The hand is less likely to protect itself from unexpected collision with this small amount of compression. After taking these into considerations, our final choice is the pretension case.

Another point to mention is that this antagonist arrangement does not give nonlinear stiffness as those in VSAs; it is for bi-directionality. Nonlinearity is realized by tricks of geometry of linkage shapes, which will be discussed in Section II-C and II-D.

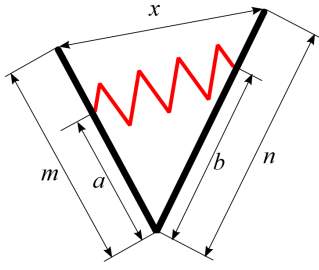


Fig. 3: Basic design idea. Length is defined as x in the figure. A rotating joint connects left and right bar.

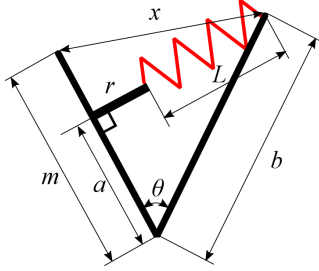


Fig. 4: Final design sketch.

C. Stiffening Behavior from Geometry

Our design adopts geometry to generate nonlinearity using linear components. With limited available space, the basic idea comprises of two links and an extension spring. Remind that we care stiffening effect during extension, and for this step we ignore the bi-directionality (*i.e.* antagonistic arrangement). We hope that a smart way of asymmetrically mounting an ordinary linear spring (as in Fig. 3) will give a stiffening effect that we desire.

A reader might suggest putting a torsion spring at the joint, eliminating the use of extension spring. From mechanical structure, this idea is preferred: it should provide nonlinearity, and is more elegant. The pity is no such a torsion spring could be found that is both strong and compact.

By modifying a, b, m, n in Fig. 3, a design according to this naive basic idea did give a stiffening behavior in a certain region, but it failed to satisfy required starting length (1.5 in) and ending length (1.75 in). This issue was solved by modify shapes of linkages. After several trials, the final shape is sketched in Fig. 4. To reduce dimensionality of design space, lengths of n and b in Fig. 3 were set equal.

Force-length and stiffness-length relation were deduced by principle of virtual work. The link is 1 degree of freedom, and generalized coordinate is chosen to be θ . Terms of use are in shown Fig. 4.

Write x as a function of θ ,

$$x = \sqrt{m^2 + b^2 - 2mb \cos \theta} \quad (1)$$

$$\delta x = \frac{bm \sin \theta}{\sqrt{b^2 + m^2 - 2bm \cos \theta}} \delta \theta \quad (2)$$

L as a function of θ ,

$$L = \sqrt{a^2 + r^2 + b^2 - 2\sqrt{a^2 + r^2}b \cos \left[\theta - \arctan \frac{r}{a} \right]} \quad (3)$$

$$\delta L = \frac{b\sqrt{a^2 + r^2} \sin \left[\theta - \arctan \frac{r}{a} \right]}{\sqrt{a^2 + r^2 + b^2 - 2b\sqrt{a^2 + r^2} \cos \left[\theta - \arctan \frac{r}{a} \right]}} \delta \theta \quad (4)$$

Apply principle of virtual work,

$$F \delta x = T \delta L \quad (5)$$

where $T = k(L - L_0)$, with k is stiffness of spring and L_0 is its original length. Plug (2) (3) (4) into (5), F can be represented as a function of θ ,

$$F = \frac{\delta L}{\delta x} T \quad (6)$$

$$= f_1(\theta; a, b, m, r) \quad (7)$$

where a, b, m, r are design parameters, and will be determined. As θ is a function of x ,

$$\theta = \arccos \frac{m^2 + b^2 - x^2}{2mb} \quad (8)$$

Plug (8) into (7), F can be represented as a function of x ,

$$F = f(x)|_{a,b,m,r} \quad (9)$$

And stiffness-length relation can be generated by taking derivative of (9) with respect to x .

$$k(x) = \frac{\partial F}{\partial x}|_{a,b,m,r} \quad (10)$$

Parameters a, b, m, r were determined using constrained non-linear programming, maximizing stiffness gain over all allowed range. Constrains from size and mechanical properties were included as inequality constraints. Final results were modified manually from the optimization result to fit other mechanical requirements that were not able to express mathematically.

D. How Profiles Change with respect to Variables

Six design parameters influence the resulting profiles. Two of them k and L_0 come from spring selection; four of them a, b, m and r come from linkage shapes. One has to notice that although the four link parameters can be relatively accurate with our chosen manufacturing methods, the two from the spring may deviate from product data. In order to determine variables during design, it is helpful to analyze how profiles change when one variable changes with the other five fixed. Note that variable determination and mechanical realization are mutually influenced, and that final values are found by iterations.

Table I summarizes results from sensitivity study. Each parameter increases within a neighborhood around its final value. '+' means increase in nonlinearity or overall force as the parameter increases, '0' little, and '-' negative. This analysis is of help in finding out a good initial condition for optimization, and is also helpful in afterward manual modifications.

TABLE I: influence of design parameter values

variable	stiffening	force	final choice
k	+	+	11.21 N/mm
L_0	0	-	12.70 mm
a	0	+	7.62 mm
b	0	+	23.66 mm
m	-	-	38.10 mm
r	+	-	7.62 mm

E. Hardstops

Hardstop is included in the design. If the link is compressed or extended into pre-defined length limits, a hardstop will set length at the limit values. When length limit is achieved, the link will become uni-directionally rigid, which means that it cannot be extended (compressed respectively), and can be treated as a rigid link if it arrives extension (compression respectively) limit. Theoretically speaking, force and stiffness jump to infinity at hardstops.

III. MECHANICAL REALIZATION

A. Design Requirements

The design is limited by various constraints. First, the link should be compact enough to be installed in Simple Hand. Second, it should follow almost exact starting and ending length of the old version, as these values were results of least manufacturing error optimization design principle. Third, it should be as frictionless as possible. Forth, least manufacturing and easily accessible parts are preferred.

B. Spring Selection

Springs are the major coming of compliance, and we cannot make them by ourselves. These reasons make springs be the first parts to select. The requirement from Simple Hand philosophy that springs are off-the-shelf prevents us from picking any k and L_0 ; in fact these values are discrete, pre-determined, paired, and are likely to vary from rated values. Moreover, the requirement of small sizes further limits the choices of spring products that we can use. All these make spring selection a difficult problem.

Extension spring gives overall profile, making it the dominant spring. From Table I, a larger k is preferred for greater nonlinearity and force. From Table I, a smaller L_0 is preferred for greater force. Compression spring deviates the profile, increasing stiffness around the link's free length. When generating same amount of force, a harder compression spring will have smaller region of deviation but larger deviation in stiffness; a softer compression spring will deviate the profile in a smaller amount but in larger region. Here we made a tradeoff by selecting one with median stiffness and maximum force from all available choices.

C. Mechanical Realization

Links are designed to be comprised of 3 layers, so as the design process is converted from 3D to 2D to ease design iteration, and they can be laser-cut or water-jetted to ease manufacturing. Fig.5 shows the links after installation.

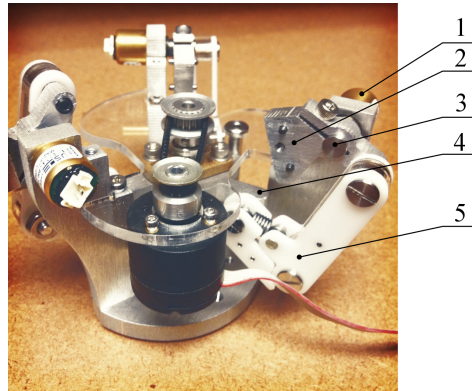


Fig. 5: Installed links on Simple Hand. (1) encoder, (2) finger lever, (3) encoder axis, (4) spider, and (5) compliant link.

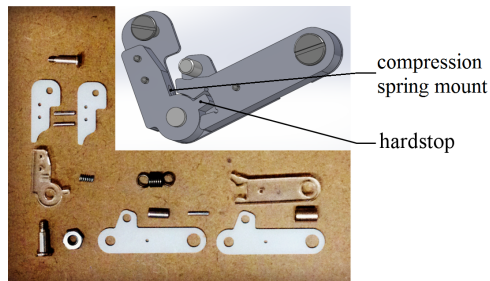


Fig. 6: CAD model and components of a compliant link. Springs and upper layer of linkages are removed in CAD for better visualization. The CAD clearly shows what hardstop looks like.

Fig.6 shows components of a compliant link, especially the compression spring mount and the hardstop that are blocked in Fig.5.

Currently, bar material are chosen to be Acrylic and Delrin. These material can be easily manufactured by laser-cut, and hopefully will have a low friction. Another benefit is that they can protect other more expensive parts of Simple Hand. At this time, hardstops act as safety switches. If there is a big unexpected collision, the cantilever beam of a hardstop will break, allowing the link to move freely, thus protecting other parts.

Details on parts selection are in Table II.

IV. EXPERIMENT

A. Experiment Setup

Experiment setup is shown in Fig. 7. The link was installed between an ABB IRB-140 manipulator and an IMADA ZTS-110 force gauge. The force gauge had an range of 500N and an accuracy of $\pm 0.2\%$ F.S. and ± 1 LSD. During experiments, IRB-140 would move upwards 1mm each time. Photos were taken after each movement, and were later used to measure link length. Link lengths were determined from photos with software ImageMeasurement. The visual measurement was supposed to have a precision of ± 0.5 mm. A safety string, which would broke at approximate 40N, was used to protect the link from overload.

TABLE II: Selection of Parts

Parts	number	detail
extension spring	1	$k = 11.6\text{N/mm}$, $L_0 = 14.6\text{mm}$
compression spring	1	$k = 5.7\text{N/mm}$, $L_0 = 6.35\text{mm}$
upper layer for leg 1	1	1/16" Delrin, laser-cut
middle layer for leg 1	1	1/4" Acrylic, laser-cut
lower layer for leg 1	1	1/16" Delrin, laser-cut
shoulder screw for leg 1	1	1/8" × 3/8"
upper layer for leg 2	1	1/16" Delrin, laser-cut
middle layer for leg 2	1	1/4" Acrylic, laser-cut
lower layer for leg 2	1	1/16" Delrin, laser-cut
shoulder screw for leg 2	1	1/8" × 3/8"
sleeve bearing	1	1/4" OD, 3/16" shaft
dowel pin	1	3/16" × 3/8"
spring pin	3	1/16" × 3/8"
nut	1	# 4-40

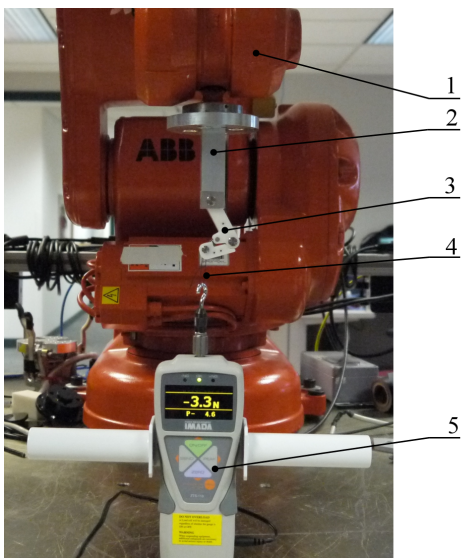


Fig. 7: Experiment setup. (1) ABB IRB-140 manipulator; (2) link fixer; (3) compliant link; (4) safety string; (5) IMADA ZTS-110 force gauge.

Experiment setup had low friction. Force gauge floated on horizontal plane, eliminating influence of resolved horizontal force. These ensured that readings from force gauge approached real extension force acting on the link.

For compression, we only required that it can be compressed, without worrying what profile it should look like. So, compression profile was not included in this experiment. Instead, the amount of compression was tested, and was 4mm.

B. Experiment Result

Fig. 8 gives results of experiments.

Star and circle are data from before and after 500 stretches respectively. The two sets of data vary little, which implies that the link has good repeatability.

Free length is 39.0mm, whereas its intended value is 38.1mm (1.5in). This different is a result of less accurate manufacturing of compression spring mount. The mount was drilled manually after laser-cut, whose position and depth was not well controlled.

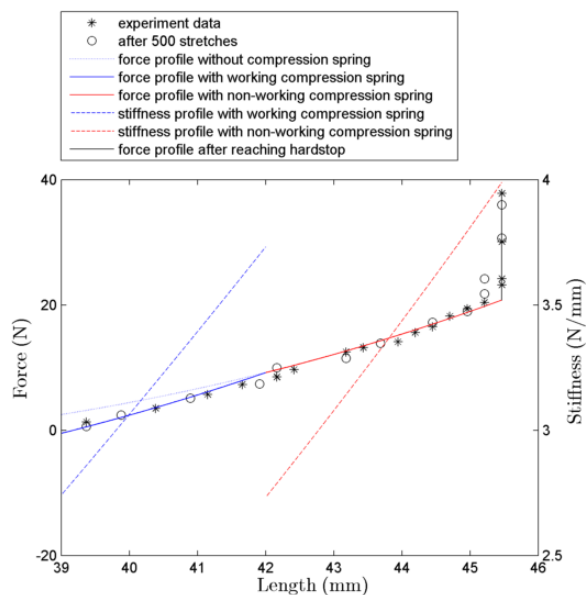


Fig. 8: Experiment results during extension and regressed profile.

Predicted force profile during extension is in solid curve. The force profile is piecewise continuous, and is painted in blue, red, and black. These three colors are with respect to three modes of link during extension: compression spring is compressed (in blue); compression is not compressed (in red); hardstop is achieved (in black).

Predicted stiffness profile according to above force profile is plotted in dash curve, and is colored as before. The gap between blue and red segments indicates mode transition due to compression spring non-working or working. From stiffness profile, it can be seen that the stiffness is piecewise increasing, although compression spring breaks the profile in the middle.

V. DISCUSSION

A. Force/Torque Sensing and Control

A compliant link with a motor encoder and a joint encoder serves as a force/torque sensor. With encoder readings and known geometry of Simple Hand, length of each compliant link can be computed. With tested profile between length and force, the force on a compliant link can be computed. As finger mount can be treated as a level, the torque on each finger is known.

Closed-loop torque control can be implemented given these computed forces. Controlling torque on one finger is easy. The whole system, viewing from the motor to one finger, can be treated as a serial elastic actuator [17] that has a nonlinear property. In this way, force/torque control problem is inherently a position control problem.

An issue with force/torque control is determining what to be controlled. As Simple Hand has one actuator and three fingers, force/torque from one single finger can be controlled at one time, leaving the other two uncontrollable. Controlling force/torque on a single finger is of little help in

manipulation. From this point, another metric of force/torque is needed. A possible answer is the sum of the three. It makes sense for us to control how firm a grasp is, in order to grasp, pivot, or drop an object. In this way, the control is better used qualitatively instead of quantitatively.

B. Anisotropy to Force Reaction

A noteworthy feature is that the sensing is only able to react to forces whose lines of action are perpendicular to joint encoder axes; resolved forces acting along joint encoder axes will not be sensed. This doesn't matter much during object-centric and hand-centric mode, in that normal forces between fingers and objects are not much different from total force, especially when finger contact surface is rigid, frictionless, and a family of line segments that are parallel to encoder axis (as those fingers designed for [18]).

However, this anisotropy does influence antenna mode. In this mode, Simple Hand should know whether it collides with an object. If it goes towards an object along joint encoder axis, Simple Hand will fail to notice the collision, and will possibly break. Adding push-buttons on both sides of fingers will enable the hand to feel collision in joint encoder axis direction.

C. Working Region of Extension Spring

With the requirements in Section III-A, working region of the link is not its sweetest region. Stiffening could be more obvious if size requirements are removed. For this paper, we decided to avoid making major changes of Simple Hand (the problem is best phrased as 'design compliant links for current Simple Hand'). However, this design methodology gives opportunities for later version of Simple Hands with more obvious nonlinear compliance. Given links with more obvious nonlinearity, the question will be reshaping Simple Hand so that it can hold more nonlinear links.

VI. CONCLUSION

In this paper, a non-linear compliant link structure that is bi-directional and stiffening is presented. It utilizes ordinary linear springs to generate non-linearity. Its mathematical model is derived, and it is realized with cheap parts and easy manufacturing. Experiment results validate its non-linearity and repeatability. This nonlinear behavior is aimed to assist Simple Hand's grasping. This points towards future work on effects of passively varying nonlinear compliance in simple gripper manipulation.

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