Soft robotic finger with variable effective length enabled by an antagonistic constraint mechanism

Xing Wang$^{1,2}$ and Hanwen Kang$^{3,4,*}$

$^{1}$ Laboratory of Motion Generation and Analysis, Monash University, Melbourne, Australia
$^{2}$ Robotics and Autonomous Systems Group, Data61, CSIRO, Brisbane, Australia
$^{3}$ College of Engineering, South China Agricultural University, Guangzhou, People’s Republic of China
$^{4}$ Foshan-Zhongke Innovation Institute of Intelligent Agriculture and Robotics, Foshan, People’s Republic of China

E-mail: hanwen.kang@outlook.com

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Abstract

Compared to traditional rigid robotics, soft robotics has attracted increasing attention due to its advantages in compliance, safety, and low cost. As an essential part of soft robotics, the soft robotic gripper also shows its superior while grasping objects with irregular shapes. Recent research has been conducted to improve grasping performance by adjusting the variable effective length (VEL). However, the existing VEL function achieved by mechanisms such as multi-chamber design or tunable stiffness shape memory material requires a complex pneumatic circuit design or a time-consuming phase-changing process. This work proposes a fold-based soft robotic finger with VEL function from 3D printing. It is experimentally tested and modeled by the hyperelastic material property. Mathematic and finite element modeling is conducted to study the bending behaviour of the proposed soft actuator. Most importantly, an antagonistic constraint mechanism is proposed to achieve the VEL, and the experiments demonstrate that better conformity is achieved. Finally, dual-mode grippers are designed and evaluated to demonstrate the advances of VEL on grasping performance.

Keywords: soft actuator, 3D printed actuator, variable effective length, constraint mechanism

(Some figures may appear in colour only in the online journal)

1. Introduction

Soft robotics has been extensively studied recently due to its inherent advantages of being compliant, robust to impact, flexible, and safe compared to traditional rigid robotics [1]. The soft bending finger demonstrates excellent applicability in the design and manufacture of the soft prosthetic hands [2], soft robotic gripper [3, 4], soft prosthetic device [5], soft artificial fish [6], rehabilitation device [7], and various types of locomotion robots [8, 9]. Among these, the soft robotic gripper shows advantages in grasping objects with different shapes and weights, which make them excellent candidates for applications like agricultural harvesting [10, 11], industrial food and fruit processing [12, 13], etc. The soft robotic bending actuator can be classified into three main categories based on its bending principle: fibre-reinforced soft actuator [14], PneuNet [15], and eccentric actuator [16], corresponding to multi-material asymmetry, pleated structure asymmetry, and eccentric void asymmetry principle respectively.
Pioneering research has been conducted on the development of dexterous soft robotic grippers, which aims to improve the performance of the gripper in terms of the allowable grasping size, grasping force, etc. Park et al. [17] proposed a hybrid PneuNet gripper for improved force and speed grasping application. Zhou et al. [18] designed a three-segment soft gripper to grasp objects of more sizes. Afterwards, he proposed another 13 degree of freedom (DoF) soft hand for dexterous grasping [19]. In addition, Wang et al. proposed the fluid robotic arm with three fiber reinforced hydraulic chambers to achieve 3 DoF bending motion [20]. However, the multi-segment/DoF design typically requires multi-active channels, tubing, and multi-valve pneumatic systems to control individual segments for a desired effective length, making the pneumatic control system significantly complex and bulky. Besides, the variable effective length (VEL) is also explored for the soft finger with one whole segment to achieve better conformity of the objects, allowing better grasping in various shapes and weights. Hao et al. [21] proposed a gripper that can achieve VEL by selectively softening shape memory polymer (SMP) sections via a flexible heater. Even the softening can be realized within 0.6 s; the cooling of SMP takes up to 14 s. The exact timing issue limits the broader application of an SMP-enabled VEL soft actuator designed in [22, 23].

This study introduces a soft folded-based bending actuator with a VEL function enabled by an antagonistic constraint mechanism (ACM). The VEL is bio-inspired by the tendon arrangement in the human finger as shown in figure 1, where different tendons are fixed on different phalanges. The tendons can be either actively tightened or passively fixed. Different tendon arrangement helps the finger achieve variable effective bending length, which benefits the grasping of various objects. This VEL in the proposed soft actuator is also enabled by the selectively placed tendon constraint on the top side of the soft actuator, which allows a design without a time-consuming reprint process. There are some researchers that implemented the hybrid pneumatic and tendon mechanism in soft robotics. For example, Li et al. presented a pre-charged pneumatic actuator, which is actuated by pre-charged air pressure and retracted by tendons [25]. Its bending angle changes when the tendons are pulled or released. Shiva et al. proposed a soft manipulator that was actuated by pneumatic pressure and tendons. Tendons were connected to the distal ends of the robot section and run along the outer sleeve allowing the sleeve to bend when the corresponding tendon was pulled [26]. This work is different from existing work because the tendon is not used as an actuation unit but it can be customized to a certain length and integrated with the soft robotic finger or it can be constrained by the motor to maintain its length.

In addition, the stress–strain curve of NinjaFlex is experimentally determined due to its nonlinear property as a hyperelastic material. Experiments are also conducted on the bending motion of the soft finger with VEL enabled by tendon constraint. The main contributions of this research work are as follows:

- Mathematically modeling with the hyperelastic property of NinjaFlex is derived for the fold-based soft actuator to study the bending angle under various input pressures.
- VEL is achieved with fold-based design by an ACM.
- A two-mode gripper is designed and tested to be capable of grasping and holding objects with various weights and shapes.

2. Design and manufacture

The soft actuator was designed in Solidworks (Dassault Systems Solidworks Corp.), as shown in figure 2. The computer aided design (CAD) model was then sliced in PrusaSlicer. The key printing settings that affect the airtight of the soft finger were sourced from our previous work [27, 28], then tuned and tested to fit this manufacture. After testing, a low-cost fused deposition manufacturing (FDM) 3D printer, Prusa Mk3s, was utilized to print the proposed soft finger with a commercially available filament, NinjaFlex.

The soft finger was integrated with the 3D-printed rigid mounts, as shown in figure 2. They are three holes within the 3D printed mount, where the bourdon tubes were slid in for the tendon to sit. These bourdon tubes also reduce the potential friction between the rigid mount and the tendon during the actuation process. A commercially available stiff tendon (26.4 kg diameter \(\times\)0.342 mm) was slid into the tendon guide to provide constraints. One end was fixed on the soft finger by making a node and gluing on the soft actuator, and the other end could be a free end or connected to the actuation mechanism, as shown in figure 3. The section that is constrained by the stiff tendon (red line) would remain in a straight configuration under actuation while the rest of the finger bends. The cross-section view of the design with detailed parameters is shown in figure 4. The detailed parameters and values are also shown in table 1.

The soft finger is expected to bend uniformly under inflation pressure due to the fold-based geometry design. In addition, the tendon (in yellow) as shown in figure 2, can be selectively fixed on the top side of the robotic finger where there is no strain-limiting layer. The other end of the tendon is controlled by motors. A candidate of the fixed point on the soft finger is illustrated and highlighted in the red dot in figure 2. This fixed point can be tuned manually to vary the number of segments.

![Figure 1. Tendon arrangement in human finger [24].](image-url)
that need to be constrained. A VEL can be programmed in this case.

3. Mathematical modeling

3.1 TPU characterization and material model

The thermoplastic polyurethanes (TPU) characterization is based on Yap et al [29]. However, even with the same fabrication material Ninjaflex, the hyperelastic material model can be slightly different, which may affect their predicted performance. In this case, we performed the tensile test, FEM simulation and further experimental tests on our proposed design.

To find the stress–strain relationship of the hyperelastic material, Ninjaflex, an uniaxial tensile test was performed on the dumbbell samples. It needs to be noticed that the bending motion of the proposed fold-based design is caused by the expansion of the walls that are printed longitudinally. So the materials are mainly experiencing tension in the longitudinal direction. The dumbbell samples are then printed in the
3.2. Finite element modeling

With the material property defined, it is feasible to perform finite element modeling to study the bending motion of the soft robotic finger. Firstly, the CAD model is saved as a step format and imported into the simulation software Abaqus. Next, the material property needs to be defined with the parameters from the previous TPU modeling. The section can be added to the model after creating and assigning the material property. Two surfaces are created named inner and the contact surface, while the former is selected inside the cavity, and the latter enables self-contact interaction during bending motion. Solid tetrahedral quadratic hybrid elements (element type C3D10H) are used to mesh the soft finger. Various static pressures are input and applied on the inner surface as the load, and the ENCASTRE boundary condition is applied at the proximal end.

3.3. Bending angle

The bend angle that defines how much the actuator curls is treated as one key index to evaluate its performance [15]. For the fold-based soft actuator, it can be concluded from the preliminary simulation that the bending motion occurs due to the elongation of the top wall of the connector. To calculate the wall expansion, each wall is modeled as a rectangular plate with four edges clamped [30, 31]. The maximum deflection occurs in the centre of the plate, while its value is affected by the plate thickness, aspect ratio $a/b$, and proportional to $(a/2)^\alpha$ [32]. The variables $a$ and $b$ are $h_w$ and $W_t$ respectively, as shown in figure 4. To model the expansion of both vertical and top walls, we adopt the equivalent connector conversion from Lotfiani et al [33] while keeping the rest of the finger dimensions the same. The equivalent connector with the updated dimensions is as shown in figure 7. The dimensions for the equivalent connector $x_e$, $h_e$, and $t_e$ can be expressed with the actual dimension of the connector $l_c$, $h_1$, and $t_w$ [33]:

$$x_e = \frac{a}{2} + l_c$$  \hspace{1cm} (1)  

$$h_e = \frac{a}{b} \left[ h_1 + \left( \frac{a}{2} \right)^\alpha \right]$$  \hspace{1cm} (2)  

$$t_e = \frac{t_w + t_c}{2}$$  \hspace{1cm} (3)

Another assumption is that all the energy is assumed to store at a distance of $h_{ve}$ from the bottom layer, which simplifies the structure from figures 7(b) and (c):

$$V_{tt} = 2v_s + v_t + v_b$$  \hspace{1cm} (4)  

$V_{tt}, v_s, v_t, v_b$ are the total volume, volume at two side, top side and bottom side, respectively:

$$h_{ve} = 2v_s * h_t + v_t * h_b + v_b * h_b$$  \hspace{1cm} \frac{V_{tt}}{V_{tt}}$$  \hspace{1cm} (5)  

The total potential energy can be expressed as the sum of the work done by air and the strain energy stored in the walls:

$$W = W_{air} + W_{str}$$  \hspace{1cm} (6)
The potential energy caused by inflation pressure is:

\[ W_{air} = \int M_p(\phi) d\phi. \]  \hspace{1cm} (7)

The constant moment \( M_p \) caused by the constant pressure is assumed to act on the soft finger with a distance of \( d \):

\[ M_p = PA d \]  \hspace{1cm} (8)

\[ d = \frac{1}{2}(H_1 - h_{ee}). \]  \hspace{1cm} (9)

Upon inflation, each equivalent connector forms a curved shape with a radius of \( r \) and angle of \( \phi \), as shown in figure 7(d):

\[ \phi = \frac{x_e}{r} = \frac{x_e}{h_{ee}} (\lambda - 1). \]  \hspace{1cm} (10)

By combining equations (7)–(10), we have the work done by the input pressure as follows:

\[ W_{air} = PA \cdot \frac{(H_1 - h_{ee}) \cdot x_e}{2} \cdot \frac{x_e}{h_{ee}} (\lambda - 1). \]  \hspace{1cm} (11)

The strain energy stored in the walls can be expressed as:

\[ W_{str} = \int E_{str} dV_{str} \]  \hspace{1cm} (12)

\[ E_{str} = \sum_{p,q=0}^{N} C_{pq} (I_1 - 3)^p (I_2 - 3)^q + \sum_{m=1}^{M} \frac{1}{D_m} (J - 1)^{2m} \]  \hspace{1cm} (13)

We assume that the NinjaFlex is incompressible, so \( J \) equals to 1 and the second component is zero. By combining equations (12) and (13), the strain energy stored in the walls can be expressed as:

\[ W_{str} = [C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + C_{11}(I_1 - 3)(I_2 - 3) + C_{20}(I_1 - 3)^2 + C_{02}(I_2 - 3)^2] \cdot V_T. \]

While \( I_1, I_2 \) are the first and second deviatoric strain invariants, and they can be calculated with equations:

\[ I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \]  \hspace{1cm} (14)

\[ I_2 = \lambda_1^2 \lambda_2^2 + \lambda_2^2 \lambda_3^2 + \lambda_3^2 \lambda_1^2. \]  \hspace{1cm} (15)

The material is incompressible, so \( \lambda_1 \cdot \lambda_2 \cdot \lambda_3 = 1, \lambda_1 = \lambda, \lambda_2 = \lambda^{-1}, \lambda_3 = 1. \) When the soft finger bends to a certain angle, it is in equilibrium state, so the gradient of the potential energy W.R.T \( \lambda \) equals to zero, which can be written as:

\[ \frac{\partial W_{air}}{\partial \lambda} + \frac{\partial W_{str}}{\partial \lambda} = 0 \]  \hspace{1cm} (16)

\[ \frac{\partial W_{air}}{\partial \lambda} = PA \cdot \frac{(H_1 - h_{ee}) \cdot x_e}{2} \cdot \frac{x_e}{h_{ee}} \]  \hspace{1cm} (17)

\[ \frac{\partial W_{str}}{\partial \lambda} = 2(C_{10} + C_{01}) \cdot (\lambda - \lambda^{-3}) + 4(C_{20} + C_{11} + C_{02}) \cdot (\lambda - \lambda^{-3}) \cdot (\lambda^2 + \lambda^{-2} - 2). \]  \hspace{1cm} (18)

By combining equations (1)–(5) and (16)–(18), the bending angle \( \phi \) for one connector can be solved. The overall bending for the soft finger is the sum of all connectors, then we have:

\[ \theta = n \cdot \phi. \]  \hspace{1cm} (19)

From equation (19), the bending angle is proportional to the number of connectors/folds. This means that a VEL can be potentially achieved by varying the value \( n \), which is the number of connected segments/folds. Our proposed mechanism selects different constrain points on the soft finger to vary the number of segments/folds to tune the effective length.
4. Experimental results and discussion

4.1. Test of bending angle

Soft bending actuators have various bending states under different inputs. To find out the relationship between the input pressure and the bending angle of this 3D printed fold-based design, the test of bending angle is set up as shown in figure 8.

The soft finger is fixed at the proximal end and placed horizontally on a grid board. This placement is to eliminate the effect of gravity on the in-plane bending motion. Various pressure inputs are regulated by a pressure regulator (SMC Corporation, Australia) and then applied to the soft finger with a step of 10 kPa. An RGB camera (Realsense D455, Intel) is fixed on the tripod to capture the image at a certain bending state, which will be further processed to obtain the value of the bending angle. The experimental data and the FEM result under certain pressures can be seen in figure 9. The mathematical result is obtained from equation (19). Besides, a detailed comparison of the experimental results, FEM, and the mathematical modeling are also shown in figure 10. It can be seen that the mathematical modeling matches the experimental results well under lower pressures. While the differences are slighter and larger under higher pressure values (more than 110 kPa). The geometry parameter $\alpha$ is fine-tuned based on the results to get the best fit mathematical model. The maximum error between the prediction and the experimental result is 6.3%. While the FEM demonstrates higher differences between the experimental results, especially under higher inputs. This might be caused by the relatively softer material property defined by the TPU uniaxial test.

4.2. Variable effective length

This work proposes an ACM to enable a VEL. It is designed to constrain the tendon guide side, limiting the bending motion of a certain number of folds/segments. The fundamental idea is to selectively choose the fixed point of the tendon. With the antagonistic force from the longitudinal direction of the tendon, certain predefined segments/folds can be constrained, preventing the bending motion. Simulation is also conducted...
Figure 10. Comparison of bending angle data between experiments, modeling, and FEM.

Figure 11. VEL of the soft finger with ACM, the green line indicates the constrained segments.

Figure 12. Conformity test of the VEL soft actuator.

by adding additional constraints to allow various bending patterns, as shown in figure 11. The ACM is realized by tendon constraint, as highlighted in the green line in figure 11. The proposed ACM can achieve VEL and potentially conform to objects of different contours. To investigate shape conformity, several samples with various curvatures are utilized as the test samples. The effective length of the soft finger is selected based on the curvature of the samples. As shown in figure 12, the full effective length (FEL) shows the best fit to a constant curvature sample, while the ACM soft finger conforms to the other irregular samples well based on the area of contact. This is due to the advances of ACM, which extends the soft finger from a single bending profile to versatile bending shapes.

4.3. Gripper design and grasping tests

The ACM mechanism enables the soft robotic finger with VEL property, with which a certain effective length can be tuned for a specific object. To achieve this, we design a soft robotic gripper with two fingers facing each other. The design for the gripper is shown in figure 13. Both actuators are actuated with positive pneumatic pressure, while the ACM is enabled by tendon-fasten. To be specific, one end of the tendon is fixed by a step motor (Bipolar, NEMA 17) once the shorter effective length of the actuator is required. The gripper is designed to have two modes: the full-bending mode and the tip-bending mode. While the tip-bending mode is achieved by presetting the fixed point on the third last fold on the soft finger. This fixed point can be adjusted or added quickly for a tunable effective length before the grasping tasks.

We mounted the gripper on a commercially-available industry robotic arm, UR5, to perform grasping tasks. The soft gripper first demonstrates its grasping capacity by gripping objects with various shapes by both pinch and power grasp, as shown in figure 14. The gripper successfully picked up objects with pinch and power grasps, weighing from 22 g to 435 g.

To further investigate the effect of VEL on the soft finger, the tendon position is initially locked by the step motor. As a result, only unconstrained segments are free to bend. The comparison between the full bending and the bending with different effective lengths is shown in figure 15. It can be seen from the grasping patterns that the contact area can be increased significantly when the soft finger switches to different effective lengths for a specific object. The increase in the contact area can benefit the envelope grasping and be potentially utilized to receive more contact information when the sensing mechanism is integrated. The benefit of the VEL on the grasping force is evaluated by a pull-out force test, as shown in figure 16. Cylinders with different dimensions are grasped and held by the soft gripper in two separate modes. The weights are hanging to provide the gravity force to pull the cylinder out of the gripper. The critical pull-out force is utilized as an index to evaluate the grasping force. A detailed comparison between modes when grasping cylinders of different dimensions is shown in figure 17(a). From the results, a larger force is required to pull the cylinder out with the increase of input pressure or the diameter of the cylinder. This is because a
Figure 13. The detailed design of proposed soft gripper with key components labelled, (a) two-finger gripper (b) three-finger gripper.

Figure 14. Grasping test of (a) rectangular plate, 22 g, (b) wooden block, (202 g), (c) knife, 78 g, (d) wooden block (207 g), (e) water bottle spray (435 g).
Figure 15. Grasping of rectangular plate and sphere with full FEL (a) (c), and constrained effective length (CEL) (b), (d).

Figure 16. Setup for the test of pull-out force: the weights are applied to pull the cylinder out of the gripper at different inputs.
Figure 17. Results for pull-out force test (a) pull-out force with various input pressures for soft finger with FEL, (b) comparison between the pull-out force between FEL and CEL.

Figure 18. (a) Test setup for three-finger gripper, (b) pull-out force results for three-finger gripper.

soft finger can generate more grasping force with the increase of pressure or the contact area. From figure 17(b), varying the effective length of grasping can secure the grasping motion, as more force is required to pull the target out of the gripper. An increase of 13.93% and 10.63% in the pulling force is observed while grasping cylinders with a diameter of 60 mm and 65 mm, respectively.

To further evaluate the benefits of VEL, a three-finger gripper is tested by pulling a test sample out of the gripper in a lateral direction, as shown in figure 18. The VEL enables the soft gripper with a larger contact area with the grasped object, which results in more stable grasping. The pull-out force is used to evaluate the benefits of VEL. There are two blocks with a height of 74 mm and 84 mm utilized, and each of them has a coarse and smooth surface to vary the surface condition. As shown from the results, the pull-out force is smaller on a smooth surface due to a smaller coefficient of friction. The pull-out force becomes larger when the VEL is enabled while pulling the block out of the three-finger gripper for both blocks. On the smooth surface the pull-out force increases by 36.9% and 23.6% respectively for blocks with 74 and 84 mm lengths.

5. Conclusions

To achieve a broader application of the soft robotic gripper on grasping objects with various shapes and weights, this work proposes a VEL soft robotic finger enabled by ACM. The robotic finger is made from direct 3D printing, simplifying the manufacturing complexity compared with the multi-step casting method. The NinjaFlex utilized is also experimentally tested to provide more detailed and appropriate material properties for the modeling. Energy-based mathematical modeling is proposed to model the bending angle by considering the hyperelastic property of NinjaFlex. The experimental results indicate that the proposed model can predict the bending behaviour within a maximum error of 6.3% under the maximum operation pressure (130 kPa). The VEL is also superior when grasping non-constant curvature samples based on the area of contact. Both two-finger and three-finger grippers are finally designed to test the grasping performance, which can lift objects of various shapes.

There are still limitations to the proposed ACM; for example, the VEL in the middle segments of the soft finger currently requires manual adjustment. Even though it is much more efficient than redesigning and reprinting the soft actuator, the automatically programmed VEL function will still benefit a more intelligent grasping. Future research will be focused on enabling the automatic switching of the constraint point on the soft actuator.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).
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ORCID iD

Xing Wang  https://orcid.org/0000-0002-8676-7821

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