A Soft-rigid Hybrid Actuator with Multi-direction Tunable Stiffness Property

Jianfeng Lin, Ruikang Xiao, and Zhao Guo, Member, IEEE

Abstract—The ability to maintain compliance during interaction with the human or environments while avoiding the undesired destabilization could be extremely important for further application in practicality for soft actuators. In this paper, a soft-rigid hybrid actuator with multi-direction tunable stiffness property was proposed. The multi-direction tunable stiffness property, which means that the stiffness of multiple directions can be decoupled for modulation, was achieved in two orthogonal directions, the bending direction (B direction) and the direction perpendicular to bending (PB direction). In the B direction, the stiffness was modulated through the antagonistic effect of the tendon-air hybrid driven; in the PB direction, the jamming effect brought by a novel structure, the bone-like structure (BLS), reinforces the PB-direction stiffness. Meanwhile, in this paper, the corresponding fabrication method to ensure airtightness was designed, and the working principle for the two mechanisms of the actuator was evaluated. Finally, a series of experiments have been conducted to characterize the performance of the actuator and analyze the stiffness variation in two orthogonal directions. According to the tests, the maximum fingertip force reached 7.83N. And the experiments showed that stiffness in two directions can be tuned respectively. The B-direction stiffness can be tuned 1.5-4 times with a maximum stiffness of 1.24 N/mm. The PB-direction stiffness was enhanced about 4 times compared with the actuator without the mechanism, and it can be tuned decoupling with a range of 1.5 times.

I. INTRODUCTION

In recent years, due to the increasing need for the robotic system to interact with the human or constructed environment, the soft robots which are compliant and flexible attract scientists’ attention [1]. Therefore, soft actuators are widely used in different robotic systems. To ensure safety during the interaction with humans, soft manipulators [2]–[4], soft rehabilitation exoskeletons [5], [6], and soft prosthetic hands [7] were proposed to replace the rigid ones. Meanwhile, in the field where the robots need to deal with the complexity of contacting subjects like grasping [8]–[11] or climbing [12], [13], the soft actuators offer an adaptive solution without a complicated control algorithm. However, due to the compliance of soft material, the external load of the soft actuator which may vary in different situations may cause undesired destabilization. For this reason, the tunable stiffness actuator is an effective solution due to its advantages for both rigid robots and soft robots.

In this framework, the active and semiactive stiffness regulation methods were proposed in the past research [14]. The active method including fluidic actuators [15], shape memory materials [16], and tendon-driven actuators [17] aims at stiffening through the antagonistic manner. The semiactive modulation represents that the stiffness is tuned by changing the property of intrinsic rigidity, such as material jamming [8], magnetorheological (MR) [18], and low melting point materials [19].

Although the shape memory materials and low melting point material are widely used to control the stiffness, the practicability is limited by their long response time. Therefore, the jamming-based mechanisms offer a solution to achieve a considerable stiffness change with a short response time. For example, Jiang et al. [20] designed a mechanism based on chain-like granular jamming to enhance the stiffness greatly with a short response time. However, the range of tunable stiffness is small, which means that it has poor flexibility and compliance.

To address this challenge, the gas-ribbon-hybrid driven actuator was proposed by Zhang et al. [21]. The stiffness of the actuator is modulated in an antagonistic way. However, because of the low original stiffness of the actuator, the destabilization in the non-bending direction especially in the direction perpendicular to bending may occur during application. To be more specific, for example, the grasping may fail when the gripper changes the orientation from the vertical plane to the horizontal plane.

Considering all the challenges, to maintain a larger range of the tunable stiffness and prevent the undesired destabilization, we proposed a new soft-rigid hybrid actuator with multi-direction tunable stiffness property (MTSA), as
Fig. 1 displays. And the property is achieved through the combination of tendon-air driven solution and a novel bone-like structure (BLS). The main contribution of this paper is to propose the design of MTSA, and the fabrication process that can improve the airtightness. Then the working principle of stiffening of MTSA was analyzed from two orthogonal directions, the bending direction, and the direction perpendicular to bending. Finally, the performances including the fingertip force and the stiffness in different directions were tested.

II. STRUCTURE DESIGN AND FABRICATION

A. Structure Design

The main structure of MTSA, as Fig. 2b shows, is composed of three major parts, the main body, bone-like structures (BLSs), and the rigid connector. The two BLSs are attached to each side of the main body, connecting to the rigid connector to form a soft-rigid hybrid structure. The MTSA is driven by a mixture of tendons and gas.

Fig. 2a displays the sectional view of the main body and the details of the soft-rigid connection. The main body includes three components: a soft contact end, the soft chamber, and the actuation tendons. To achieve compliance, the Smooth-On 0020 silicone, with a 20-shore hardness is chosen to fabricate the soft chamber with a nylon mesh inserted to limit the elongation. According to Abondance et al. [11], the contact pad will help to increase the fingertip force. Therefore, the soft contact end, which is cylindrical is made of a harder silicone (Smooth-On 0030) and glued in the front of the soft chamber to contact with the environment and objects. The actuation tendons (Kevlar) cross through the holes in both sides of the actuator and tie to the rope fittings at the end of the actuator. These holes’ centers are in the same plane as the symmetrical plane of the rigid chain. The back of the soft chamber is cast into the connector. Due to the porous structure of the connector, the airtightness of the soft-rigid connection can be enhanced. The quick connector will be connected to the rigid connector through a pipe thread.

The design details of bone-like structures are shown in Fig. 2c. There are three major parts in each BLS, rigid chain, pre-tension mechanism, and plate, connected through a fishline go across them. The fishline is fixed by two set screws in the distal segment and its path is shown in Fig. 2c in yellow. Three types of segments (PLA) constitute the rigid chain: distal segment, common segment, and proximal segment. The bulge and concavity of the common segment are semicylindrical, and the holes are perforated along the tangent of the cylinder. The segments are designed as a bone to match the size of the actuator. The pre-tension mechanism, whose components are 3D printed by nylon is to offer the pre-tightening force of BLS. The two pulleys (nylon) on each side of BLS provide a path to guide the fishline and form a...
Fig. 3. The fabrication process of the proposed MST A. (a) The first step is the fabrication of the soft chamber. (b) The second step, fit the BLSs. (c) The third step, assemble other components.

closed-loop path. One of the pulleys is connected to the slider (PLA) placed in the chute of the backward plate (PLA). By adding specific sizes of PLA blocks to change the position of the slider, the pre-tightening force of the fishline can be regulated, meaning that the stiffness of BLS can be adjusted, either. The plate, pre-tension mechanism, and rigid connector are connected by nuts and screws.

B. Fabrication

In this work, the MTSA is fabricated based on combining the porous connector with the lost-wax method. The lost-wax method is utilized to enhance the airtightness so that the allowable input pressure range of the actuator can be extended, enlarging the tuneable stiffness range. The porous sidewall of the connector reinforced the airtightness in the soft-rigid-connection boundary. The fabrication process, which is illustrated in Fig. 3 includes three steps: fabrication of the soft chamber, fitting the BLSs, and assembling other components. All the molds for casting were 3D printed with ABS.

Fabrication of the soft chamber. As Fig. 3a shows, the wax core was fabricated by pouring the melted wax into molds and demolding it after the wax was cured. To make the lost-wax process more accessible, the low melting point wax (about 70°C) was chosen. Then, the connector with the wax core fitted to it through the cylinder hole was placed in the mold. The fluid silicone was poured into the pre-closed mold. Before the silicone was cured, a nylon mesh was embedded into the bottom layer and two metal sticks were inserted through the holes in the mold. Then, the soft chamber with a wax core in it was obtained after it was cured.

Fitting the BLSs. As Fig. 3b displays, the soft chamber with wax core had been heated in the water bath to 85°C for 15 minutes. Squeezed out all the molten wax from the cylinder hole in the connector, then the soft chamber was assembled with two BLSs and the plate. Subsequently, two cover layers were cast and bonded with the soft chamber by uncured silicone.

Assembling other components. In this process, as presented in Fig. 3c, the sealing layer of MTSA and the contact end were fabricated. The sealing layer can be omitted since it was not an essential structure to improve the airtightness. The soft-rigid connection in porous connector has played the main role in reinforcing the airtightness. The actuation tendons crossed through the reserved holes and were fixed in the rope fitting. After connecting the quick connector and gluing the contact end, the MTSA was fabricated.

III. WORKING PRINCIPLE

The working principle of the multi-direction stiffness property, as Fig. 4 shows will be discussed from two directions of MTSA.

A. Bending direction

In the bending direction (B direction), as Fig. 4a illustrates the curving deformation of MTSA is driven by pressuring the chambers while keeping the tendons in a relaxed state. The bending of the MTSA is considered as a constant curvature and the bending angle can be calculated as , where is the bending angle of a pair of chambers and denotes the number of chambers. In this state, the actuator will remain the high compliance. When the stiffness enhancement is required, the tightened tendons will limit the bending trend of MTSA while the air pressure is still rising. The increased gas
pressure will improve the stiffness of the actuator in the bending direction.

B. Direction perpendicular to bending

In the direction perpendicular to bending (PB direction), as Fig. 4c and 4b display, there are two different states for stiffness modulation, the bending deformation state, and the combined deformation state, depending on the bending angles of the actuator.

In general, for these two states, the main principle can be concluded that the enhanced stiffness is achieved through solid components jamming and can be tuned by changing the pulling force to rope. As shown in Fig. 4c, the BLS whose components are connected through a close-loop rope can be treated as a beam with revolute joints. The cross section of the beam is equivalent to the cross section of the bulge of common segments. The rope provides the tension to keep the BLS tightened. Except for the fracture of BLS, the BLS might break due to the granular separation, as Fig. 4c illustrates, which will lead to a sharp decrease in the stiffness. According to the research done by [20], the BLS will operate normally under the condition that follows the below equation:

\[ F_{\text{ext}} \leq \frac{F_p c}{L} \]  

where \( F_p \) is the pulling force provided by rope and \( F_{\text{ext}} \) denotes the external force applied to the end of BLS, \( c \) represents the thickness of BLS, and \( L \) is the length of the rigid chain.

When the bending angle equal zero, that the BLS is in the bending deformation state, the BLSs assembled on each side of MTSA can be treated as a cantilever beam, as Fig. 4c shows. Therefore, the PB-direction stiffness can be enhanced. And the stiffness \( k \) of a single BLS can be estimated as the following equation, according to Euler–Bernoulli beam theory:

\[ k \propto \frac{3EI}{L^3} \]  

where \( E \) is Young’s modulus, and \( I \) refers to the area moment of inertia. The area moment of inertia \( I \) of BLS can be described as

\[ I = \frac{hb^3}{12} \]  

where \( d \) is the width of the equivalent beam of BLS. According to equation (2), the stiffness in the bending deformation state completely depends on the moment of inertia \( I \), since Young’s modulus \( E \) and length of BLS \( L \) are constants.

When the BLS is in the combined deformation state, the bending is performed, and the equivalent beam model turns into the curved cantilever beam as it is illustrated in Fig. 4c. To evaluate the factors influencing the stiffness, the curved cantilever beam can be simplified into two connecting rods as Fig. 4d shows. And Their angle of intersection is described as \( \theta \). In this state, when the external force \( F_{\text{ext}} \) is applied, the flexural-torsional deformation will occur. With small deformation, the deflection of the curved beam can be analyzed separately from the former rod and latter rod as follows:

\[ \omega = \omega_{\text{bend1}} + \omega_{\text{bend2}} + \omega_{\text{tor2}} \]  

where \( \omega \) denotes the total deflection at the distal end, \( \omega_{\text{bend1}} \) is the deflection caused by the bending of the former rod, and \( \omega_{\text{bend2}} \) with \( \omega_{\text{tor2}} \) refers to the deflection of the flexural-torsional deformation of the latter rod. For the bending deformation of two rods, the deflection can be given as

\[
\begin{align*}
\omega_{\text{bend1}} &= \frac{F_{\text{ext}}L_1}{3EI} \\
\omega_{\text{bend2}} &= \frac{M_1L_2}{2EI} \\
M_1 &= F_{\text{ext}}(L_1 \cos \theta + L_2)
\end{align*}
\]  

where \( L_1 \) is the length of the former rod, \( L_2 \) is the length of the rod, and \( M_1 \) refers to the bending moment applied to the latter rod. Then the deflection caused by the torsion of the latter rod is analyzed. To facilitate the evaluation, the torsional deformation is simplified to the geometrical model as shown in Fig. 4d, and the geometrical relationship can be described as

\[ \omega_{\text{tor2}} = L_1 \sin \theta \sin \varphi \]  

where the \( \varphi \) is the torsional angle, which can be calculated as

\[
\begin{align*}
\varphi &= \frac{TL}{G\beta hb^3} \\
T &= F_{\text{ext}}L_1 \sin \theta
\end{align*}
\]  

where \( G \) is the shear modulus, \( \beta \) is a correction parameter for rectangular section torsion that is related to \( h \) and \( b \), and \( T \) is the torque. Based on Equation (4)-(7), the relationship between \( \omega \) and \( F_{\text{ext}} \) can be obtained:

\[ \omega = \frac{F_{\text{ext}}}{hb^3} (L_1 \sin \theta \sin (A \sin \theta) + B \cos \theta + C) \]  

To better analyze the stiffness, the parameter \( \beta \) is regarded as a constant and is chosen as the value when \( h/b = 1 \). Based on the equation (8), it can be deduced that the moment of inertia plays the same role in both the bending deformation state and combined deformation state, the higher moment of inertia \( I \) brings the larger stiffness \( k \). While in the combined deformation state, the stiffness will change with \( \theta \).

To estimate the influence, the parameters of PLA properties were chosen to draw the image of the following function as Fig. 4b:

\[ f(\theta) = L_1 \sin \theta \sin (A \sin \theta) + B \cos \theta + C \]  

Because of \( k \propto 1/f(\theta) \), the stiffness in PB direction will decrease firstly and then increase with the bending angle changing from 0° to 180°.

IV. EXPERIMENTS AND RESULTS

To verify the design and characterize the ability of MTSA, the fingertip force and the tunable stiffness ability in the B direction and PB direction were tested.
A. Fingertip Force

To estimate the strength of MTSA, the fingertip force of MTSA was tested. The actuator connecting with air tubes was fixed on the aluminum frames and the distal end was aligned with the surface of the force gauge (HP-200, HANDPI Ltd., scale 0 - 200 N, accuracy ±0.5%). From our testing, the maximum input pressure is 90 kPa. Therefore, all the experiments including fingertip force testing were conducted under the safety input pressure, ranging from 0 kPa to 65kPa. The fingertip force was tested at incremental steps of 5 kPa and the average data were obtained after five repeated tests. And all the results were shown in Fig. 5.

The maximum fingertip force is 7.83N in 65kPa, indicating that a single actuator as Fig. 5 illustrates. Compared with other actuators in the same pressure, 7.83N is a relatively high value. The fabrication process which is based on the combination of the lost-wax method and porous connector ensures airtightness, increasing the range of allowable input pressure and thus resulting in a larger fingertip force.

B. Stiffness in the B Direction

The MTSA was placed in the same frame mentioned in the fingertip force section. Considering that the soft actuators, which are used for grasping usually interact with subjects through the contact end directly, the extension direction of MTSA was chosen as the evaluation direction of bending stiffness, as Fig. 6a displays. A carbon fiber tube with a 26mm diameter was used to generate the pulling force by being connected to the force gauge which was assembled on the sliding table through ropes. The sliding table was programmed to move 1mm rightward each time until the total distance reached 10mm and the corresponding pulling force during this process would be recorded. Then, the B-direction stiffness can be characterized by calculating the incremental ratio of the force and displacement.

According to the working principle, the B-direction stiffness can be tuned in different angles. Hence, the experiments of B-direction stiffness were conducted in four groups of angle, 45°, 90°, 135°, and 180°. For each angle, four groups of different incremental pressures were chosen. And every single set was repeated three times to obtain the average result. Fig. 6a draws the experimental result of the group 90°. As it shows, the relationship between pulling force and displacement is nearly linear. Therefore, all the stiffnesses were calculated as the slope of the fitted line to pulling force and displacement. To determine the magnitude of the change in stiffness more intuitively, the ratio of stiffness variation for each group was shown in Fig. 6b. From Fig. 6b, for all the four different bending angles, the stiffness was enhanced from 1.5 to 4 times, with a maximum stiffness of 1.29 N/mm, indicating that the stiffness in the bending direction is tuned successfully through our proposed mechanism. The result also showed that the tunable stiffness ranges when the bending angles were 45° and 90° were larger than when the bending angle is 135° or 180°. This indicated that the range of tunable stiffness is determined by the increased pressure since when the bending angle is 135° or 180°, the input pressure of MTSA is close to the maximum allowable pressure which limited their incremental pressure.

C. Stiffness in the PB Direction

To verify the multi-direction tunable stiffness property in the PB direction, the same platform mentioned before was utilized. And the MTSA’s side contacted with the force gauge. Based on the working principle, PB-direction stiffness can be modulated by changing the tension of the ropes of BLSs. Therefore, two weights were connected through pulleys to each BLS to quantify the ability of variable stiffness as Fig. 6c illustrates. Two kinds of weights, 0.5kg one and 1kg one, were available to combine into different weights.

Three groups of bending angles, 0°, 45°, and 90° were chosen to estimate the PB-direction stiffness. It is worth stating that although in the working principle section, the effect of enhanced PB-direction stiffness brought by BLS was mainly discussed, the stiffness in the PB direction is influenced by the coupling of the input pressure and BLSs. Hence, the experiment for each bending angle included the different increased pressures and weights to pull the rope. Five groups of weights 0kg, 0.5kg, 1kg, and 2kg and at least three groups of pressure at incremental steps of 10 kPa were conducted for each bending angle. Moreover, to compare the ability of BLS, the same input air pressure for actuator without BLSs were tested. The sliding table moved at a 2-mm interval from 0 to 40mm to control the deflection. A series of data when bending angle is 0° and the increased pressure is 0kPa is shown in Fig. 6c. From our analysis, the slope of all curves begins to decrease when the displacement is larger than 20mm because torsion deformation generated. Therefore, the PB-direction stiffnesses were calculated within the range of data that had linear characteristics. Then, the relationship among stiffness, weights loaded to the ropes, and increased pressure was shown on Fig. 6d for 0°, 45°, and 90° Respectively.
As Fig. 6d illustrates, comparisons between the PB-direction stiffness of actuator with BLSs and without BLSs confirms the enhanced stiffness property of BLS. The stiffness of actuator with BLSs is enhanced 4.2, 3.5, and 2.2 times for 0°, 45°, and 90° group than actuator without BLSs. Meanwhile, as can be seen, the stiffness increase with the weights to pull the rope and air pressure and the range of tunable stiffness are about 1.5, 1.2, and 1.2 times for 0°, 45°, and 90° group. These results proved that the PB-direction stiffness was tuned decoupling successfully. In addition, the largest stiffness when no increased pressure was input, increases when the bending angle varied from 0° to 45°, and decreases when the bending angle is 90°. This trend follows the analysis proposed in the working principle section. However, in other conditions, the stiffness did not share the same trends. This indicated the stiffness analysis model needs to be revised further. And the loose BLSs caused by the uncontrollable axial elongation of MTSA may contribute to the results. Based on the results of stiffness tests in the B direction and PB direction, it can be concluded that the multi-direction tunable stiffness property is achieved through the combination of tendon-gas-hybrid actuation and bone-like structures.

V. CONCLUSIONS

This study introduces a soft-rigid hybrid actuator with multi-direction tunable stiffness property and a specific fabrication strategy to improve the airtightness. Then the working principle of the multi-direction tunable stiffness was analyzed. To characterize its performance, several experiments including fingertip force and stiffness tests were conducted. Overall, the stiffness in both the B direction and PB direction can be decoupled for modulation in a wide range, which achieves the design concept of our proposed mechanism.

However, during our experiments and theoretical analysis, a few drawbacks of MTSA still exist. Firstly, although the working principle section has analyzed that one of the important factors is the moment of inertia, a better geometric dimension was not evaluated due to geometrical limitations brought by the soft chamber. Second, the simplification of the mathematical model of the PB-direction stiffness of BLS is rough and cannot predict the trend of changes in the experiment well. Third, though our fabrication method has improved the airtightness of the connection boundary between the solid and soft chamber, the lateral wall of the front chamber is easy to explode during pressurizing. The excessively thin wall thickness was caused by the displacement that happened at the distal end of the lost wax core since it only has one simple support.

Therefore, in our future work, the fabrication method is due to be revised and the optimization solutions for designing the MTSA considering the coupling effect of the geometrical size of the soft chamber and BLSs will be conducted. Meanwhile, the MTSA will be utilized in different practical scenarios to perform its ability to tune the stiffness decoupling, like versatile gripper and soft crawling robot.
