A Two-Fingered Force Feedback Glove using Soft Actuators

Yu Zhang, Dangxiao Wang*, Ziqi Wang, Yueping Wang, Li Wen*, and Yuru Zhang

***Abstract*-Existing force feedback gloves mainly adopt rigid actuators such as electric motors and pneumatic cylinders, which have limitations including safety issues, heavyweight, and complex transmission mechanisms. In this paper, we introduce a light-weighted force-feedback glove using pneumatic-driven soft actuators. Based on the unilateral deformable features of the strain-limiting layer in the soft actuator, the dorsal-side mounting solution along with a light-weighted linkage mechanism is proposed to produce fingertip force feedback. We applied a pre-deformation of the soft actuator to enable the back drivability and the free space sensation. We then implemented a physical prototype of a two-fingered glove. Experimental results show that the glove could achieve considerable performance in free space with small frictional force (0.58N in maximum). While simulating the constrained space, the fingertip force reaches up to 2.1N. For the future work, we plan to improve the current solution to five fingers with finger position tracking and distributed tactile sensing on the palm.**

I. Introduction

In recent years, the invention of low-cost head-mounted displays such as Oculus Rift advances the development of wearable virtual reality interaction, which proposes a strong motivation for wearable haptic feedback devices. In order to increase the immersive feeling of interaction with the virtual world, an ideal haptic feedback device should allow users to touch and manipulate virtual objects in an intuitive and direct way by using the dexterous manipulation and sensitive perception capabilities of our hands. Wearable force feedback gloves are a promising solution for producing immersive haptic sensation in virtual reality systems.

In the past thirty years, there are many developments of the force feedback gloves [1-12]. The CyberGrasp developed in 1998 and was the only commercially available force feedback glove [4]. With a 450g exoskeleton mounted on the back of the hand, the glove can provide up to 12 N forces to the fingertips. The Rutgers Master II—New Design (RMII-ND) used linear pneumatic pistons distributed in the palm for providing forces between the palm and fingers [9]. Pistons are directly attached to the fingers and provides up to 16 N forces to each fingertip. The HIRO III could provide a large range direction of force feedback and a large force output, even simulate the gravity of virtual objects [1]. Choi *et al.* developed a lightweight device that renders a force directly between the thumb and three fingers to simulate objects held in pad opposition type grasps [13]. By using brake-based locking sliders, the system can withstand over 100N of force between each finger and the thumb.

Existing gloves mainly adopt rigid actuators such as electric motors and pneumatic cylinders, which have several limitations including safety issues, heavyweight, complex transmission mechanisms, and structures.

Recently, soft material has been introduced into the development of force feedback gloves [10] [14]. Compared with rigid actuators, soft actuators have the characteristics of flexible deformation and inherent safety; therefore, it is particularly fit the applications that directly contact with human skin, such as rehabilitation devices and wearable haptic devices. Polygerinos *et al.* introduced a hand rehabilitation glove using soft actuators [14]. By using the Kevlar silk to limit the transformation in radial direction, and using the fiber-glass-mesh to limit the transformation of one side of the actuator, the actuator could bend when inflating the air into it, which could provide fingertip forces.

Inspired by the soft actuators proposed by Polygerinos et al. [14], in this paper, we introduce a light-weighted force feedback glove using pneumatic-driven soft actuators. Based on the unilateral deformable features of the strain-limiting layer in the soft actuator, the dorsal-side mounting solution along with a light-weighted linkage mechanism is proposed to produce fingertip force feedback. We applied a pre-deformation of the soft actuator to enable the back drivability performance and simulate the free space sensation.

II. Design of the Glove

A. Working Principle of the Soft Actuator

The soft actuators are composite tubular constructions consisting of anisotropic fiber reinforcements in an elastomeric matrix [14]. The main body of the soft actuator is silicone elastomer (Dragon Skin 30), which would expand uniformly when the inside elastic cavity is inflated with air. Dragon Skin 30 is selected as the material of the pneumatic actuator because it is both soft enough to bend via air-input and rigid enough to supply adequate power to drive the glove.

By reinforcing the walls of the tubular body, it is possible for the actuator to perform bending motions under fluid pressurization. Fig. 1 illustrates a fiber-reinforced soft bending actuator, which incorporates a symmetric arrangement of radial reinforcements to limit radial expansion and a strain-limiting layer to promote bending by inhibiting linear growth along a portion of the tubular body.

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Yu Zhang, Dangxiao Wang, Ziqi Wang, and Yuru Zhang are with the State Key Lab of Virtual Reality Technology and Systems, and Yueping Wang, Li Wen are with Biomechanics and Soft Robotics Lab, Beihang University, No. 37 Xueyuan Road, Haidian District, Beijing, China. 100191. (TEL: +86-10-82338273; Email: hapticwang@buaa.edu.cn, liwen@buaa.edu.cn).

A strain limiting layer such as woven material (i.e. fiberglass) is applied to the flat face of the main body. Although the material of the main body is isotropy, by gluing the non-elastic strain limit layer, the main body becomes anisotropy, so it could expand in just one direction. After gluing the fiber-glass-mesh to limit the direction of one side of the actuator, the other side of the actuator would expand more and the actuator would be bended when the inside elastic cavity is inflated with air pressure (as shown in Fig.1).

Next, radial reinforcements are added to the main body to limit its inflation in radial direction. By twinning the main body with Kevlar silk, the expansion in radial direction of the main body would be limited and the expansion in axial direction would be increased. At the same time, the intension of the actuator would intensify.

Because the actuator is controlled by high pressure air, if the pressure loses control, before the force provided by the actuator is large enough to hurt the finger, the actuator would leak and lose the ability to provide force. So the safety of the soft actuator is better than traditional rigid actuators such as electrical motors.

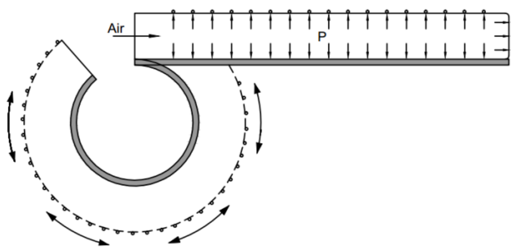

Fig.1. Inflation of the soft actuator with a strain limiting layer and radial reinforcements

B. *Concept Design of the Glove*

In order to meet the demand of haptic interaction in virtual reality, a force feedback glove needs to meet the contradictive requirements of free space and constrained space simulation.

To simulate the constrained space sensation, the friction force and the weight of the glove should be small. To simulate the constrained space sensation, the error of the applied force on fingertips should be less than the discrimination threshold of human perception on force magnitude, and the magnitude of force provided by the glove should be large enough to simulate daily grasping scenarios.

As shown in Fig. 2, to meet the contradictive demand of both the free space and the constrained space, we propose a hybrid solution of combing the soft actuator and a simple linkage mechanism with only two links.

We choose to install the soft actuator on the dorsal-side of the hand. The black and bold line on the top of the actuator represents the strain limiting layer. In order to transmit the force generated by the deformation of the actuator to the fingertip, the linkage mechanism uses only two hinges and one connecting rod to obtain a light weight and a small friction. The connecting rod is designed into L-shape to make sure the rod would not interfere with the motion of adjacent fingers. For the four fingers, the proposed mounting solution can ensure no interference between the adjacent fingers during the grasping motion. However, one remaining challenge is how to avoid the interference between the thumb and other fingers when the bending angles of the fingers are beyond a specific value.

The diameter and structure of the pneumatic actuator is determined by matching the dimensions of users' index finger, including the length and the cross-section diameter of the finger. Furthermore, we tried to enlarge the volume of the cavity in the actuator and thus to increase the power provided by the actuator.

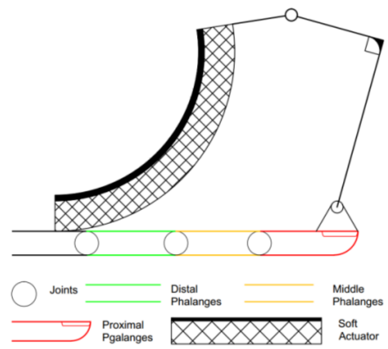

Fig.2 Concept of the glove using the soft actuator and a linkage mechanism

In free space, the user is able to move the finger freely and the resistance of the gloves should be as less as possible. We applied a pre-deformation of the soft actuator to enable the back drivability performance and simulate the free space sensation. When the actuator is not inflated by air pressure, it can freely bend in response to the rotation of the finger.

In simulating constrained space, the actuator is inflated with pressured air. The actuator will be bended to pull the mechanism, and an active force will be transmitted along the linkage mechanism to users' fingertip.

C. *Model of the Glove for One Finger*

To derive the relationship between the input air pressure and the force on the fingertip, we made several assumptions:

1. All the links are moving in the same planar surface.
2. All the forces are calculated in quasi-static process.
3. The forces on hinges, fingertip, and the actuator are all exerted on a single point.
4. Ignore the weight of all the links in the mechanism.

Take point A as origin of the coordinate system, and build the coordinate axis as Fig. 3. In this system, we need to derive the relationship between the air pressure (p) and the normal force on the fingertip (F_p).

Because the connecting rod EF is two-force rod structure, the direction of the internal force F_1 is always as same as the direction of rod. The internal force on the point E is always equal to internal force on the point F.

As shown in Fig. 3, the normal force perpendicular to the users' fingertip can be derived as

$$F_p = -F_1 \cos\theta_4 \quad (1)$$

With the coordinate value of point D and point F, the angle θ_4 could be derived as follows

$$\cos\theta_4 = \frac{l_4^2 + l_5^2 - (x_D - x_F)^2 - (y_D - y_F)^2}{2 l_4 l_5} \quad (2)$$

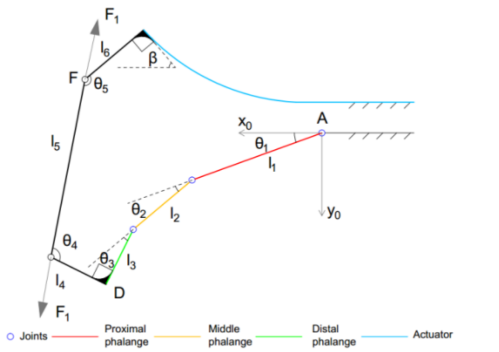

Fig.3. The schematic diagram of the glove.

Based on the schematic diagram of the glove, the coordinate value of point D and point F can be computed as

$$\begin{cases} x_D = l_1 \cos\theta_1 + l_2 \cos(\theta_1+\theta_2) \\ \qquad + l_3 \cos(\theta_1+\theta_2+\theta_3) \\ y_D = l_1 \sin\theta_1 + l_2 \sin(\theta_1+\theta_2) \\ \qquad + l_3 \sin(\theta_1+\theta_2+\theta_3) \end{cases} \quad (3)$$

$$\begin{cases} x_E = l_1 \cos\theta_1 + l_2 \cos(\theta_1+\theta_2) \\ \qquad + l_3 \cos(\theta_1+\theta_2+\theta_3) + l_4 \sin(\theta_1+\theta_2+\theta_3) \\ y_E = l_1 \sin\theta_1 + l_2 \sin(\theta_1+\theta_2) \\ \qquad + l_3 \sin(\theta_1+\theta_2+\theta_3) - l_4 \cos(\theta_1+\theta_2+\theta_3) \end{cases} \quad (4)$$

$$\begin{cases} x_F = x_G + l_6 \sin\beta \\ y_F = y_G + l_6 \cos\beta \end{cases} \quad (5)$$

$$(x_E - x_F)^2 + (y_E - y_F)^2 = l_5^2 \quad (6)$$

In Eqn. (1), one important challenge is to compute the value of the internal force F_1. The relationship between the air pressure p and the internal force F_1 can be derived by modeling the mechanical behavior of the soft actuator as

$$F_1 = g(p, x_G, y_G, \beta) \quad (7)$$

According to the above models, in order to simulate grasping a soft object, if we know the position of the fingertip and the direction of distal phalange, we could adjust the air pressure to control the force on the fingertip.

It should be noted that Eqn. (7) represents the mechanical characteristic of the soft actuator, which could be simulated by finite element analysis (in next sub-section), and then to be validated by experiments.

D. *FEA Model of the Soft Actuator*

To acquire a relationship between the air pressure p and internal force of the soft actuator, we applied the FEA modeling to investigate the mechanical properties, in particular, the bending kinematics and the force output.

For the FEA simulation, the tube of the soft actuator, which is half-circular shaped, was designated with silicone elastomer (Dragon Skin 30), as shown in Fig. 4A. Two sides of the half cylinder are sealed by two caps, separately. Then the Kevlar wire is used to restrain the radial expansion, and the Nylon layer is fixed on the bottom of the tube to restrict the extension. In the FEA simulation, the material properties and parameters of silicone elastomer, the Kevlar wire and the Nylon layer are provided in [14].

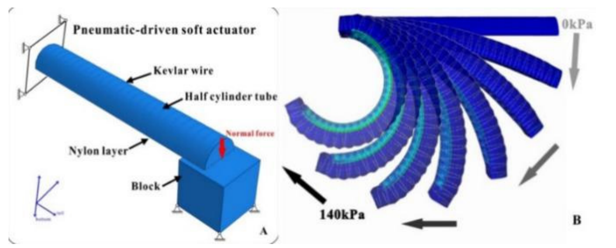

Fig.4. FEA simulation of the fiber-reinforced soft actuator. (A) The setup in the simulation environment; (B) The simulation results of the soft actuator.

The 3D model of the soft actuator was then imported into ABAQUS/Standard with one side of the actuator fixed. The pressures ranging from 0kPa to 140kPa with an interval of 20kPa were applied to the inner chamber. The bending results were shown in Fig. 4B. Furthermore, to acquire the relationship between the input pressure and the force at the tip of the actuator, we placed a block under the tip (Fig. 4A) and record the normal contact force F_n between tip of the soft actuator and the block. It should be noted the force F_n is a projection of force F_1 along the line FG. The simulated p-F_n relation was shown in Table 1.

It should be noted that the non-elastic strain of the actuator was ignored in the simulation, which might lead to the deviation between the simulation and the experimental results. More realistic simulation method needs to be explored in the future work.

Table 1 The simulation results of p vs. F_n

p (kPa)	0	20	40	60	80	100	120	140
F_n (N)	0	0.15	0.27	0.43	0.59	0.73	0.90	1.05

III. THE PHYSICAL PROTOTYPE OF THE GLOVE

We developed the physical prototype of a two-fingered glove. As shown in Fig. 5, soft actuators were mounted on the thumb and the index finger. To distinguish the difference between two actuators, we choose to dye the actuators into green and blue, respectively. The two soft actuators are fixed on the dorsal of the hand using a 3D printed fixture which could help to reduce the overall size and the weight of the glove. The fixture is sewed on the glove with the holes on the bottom of it. The links of the linkage mechanism are made by

3D-printed material. The weight of all parts on each finger is 30.8g, which is much lighter compared to other rigid gloves.

The three pictures in the left column of Fig. 6 show the snapshot of the index finger moving in the free space. The workspace of the glove is sufficiently large, and the index finger can rotate in a large range to simulate different grasping scenarios. In the bottom picture, the actuator bends only a small angle compared to its free configuration (i.e., when there is no external torque exerted on the actuator) (Fig.6). This result validates the effectiveness of the pre-deformation approach, which ensured the free bending of the soft actuator to enable the back drivability performance and simulate the free space sensation.

Detailed motion of the force feedback glove can be found in the accompanied video of this paper. In the video, it clearly shows that the user can move the two fingers freely when the cavity of the actuator was not inflated by the air pressure. The pictures in the right column of Fig. 6 show the snapshot of the index finger moving in the constrained space. In the constrained space, the unilateral bending deformation of the actuator produced resistance forces on users' fingertip. Compact electro-pneumatic regulators (ITV0030-2BL) is utilized to control the pressure of actuators.

As shown in Fig. 6, the combination of the soft actuator and the linkage mechanism can not only allow the free motion of the finger when the air pressure is absent in the actuator, but also they can transmit the force to the fingertip when the actuator is inflated by air pressure. The proposed method is effective to meet the demand of both the free and the constrained space. In the next section, we will measure the quantified performance of the force feedback glove.

IV. PERFORMANCE ANALYSIS

In this section, we performed experiments to measure the performance of the soft actuator and the force feedback glove.

A. The Performance of the Soft Actuator

In order to measure the mechanical property of the soft actuator, we used standard weight to provide external force on the tip of the actuator and measure its deformation.

As shown in Fig. 7, one end of the actuator is fixed on the table by a fixture, and a standard weight is exerted on the tail end of the actuator by a string. Seven different level of air pressure was measured. For each air pressure, seven different weights were exerted on the tail end of the actuator.

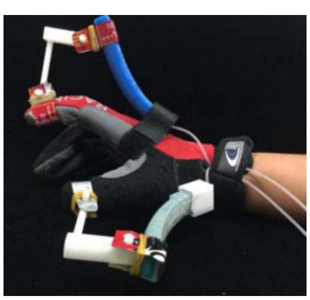

Fig.5. The two-fingered glove using soft actuators.

Fig. 6 Snapshots of the index finger and the glove. a) Simulating the free space. b) Simulating the constrained space.

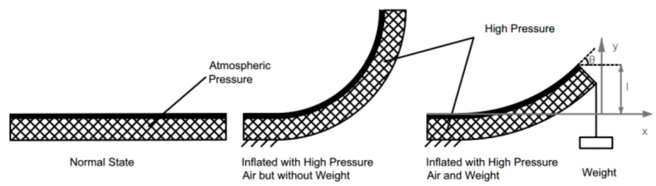

Fig. 7 Illustration of experiments for measuring the actuator performance

The relationship between the force on the tail end of the actuator and the angle of the tail end of the actuator is shown in Fig. 8. It should be noted that the force is parallel to the gravity force. For a given air pressure, there exist an approximately linear relationship between the angle and the force. For a given weight on the tail end of the actuator, with the increase of the air pressure, the angle of the tail end becomes smaller. The reason is that a bigger air pressure leads to a stronger output force, which overcomes the deformation caused by the external weight and thus increases the angle.

The relationship between the force on the tail end of the actuator and the displacement of the tail end of the actuator in vertical direction is shown in Fig. 9. For a given air pressure, there exist an approximately linear relationship between the displacement and the force. With the increase of the external load, the displacement becomes smaller, which means the deformation caused by the air inflation is reduced by the external load.

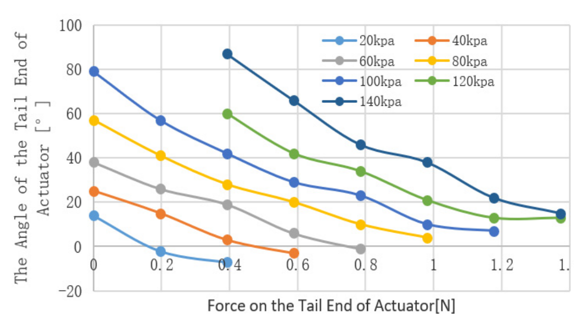

Fig.8. The relationship between the force on the tail end of the actuator and the angle of the tail end of the actuator.

Table 2 The comparison with other gloves

Performance	Glove in this paper	CyberGrasp [1]	Wolverine [13]	Jamming Tube [10]
Weight	30.8g per finger	450g	55g	20g per finger
Stiffness type	Variable stiffness	Variable stiffness	Constant stiffness	Variable stiffness
Maximum fingertip force	2.1N in specific joint angles	12N	106N	7N
Range of motion	Full hand closing	Full hand closing	20-160 mm	-
Actuation method	Pneumatic pump	Electrical motor	Electrical motor	Pneumatic pump

For a given weight, with the increase of the air pressure, the displacement of the tail end becomes smaller. The reason is that a bigger air pressure leads to a stronger output force, which overcomes the deformation caused by the external weight and thus increases the vertical displacement of the tip.

From Fig. 9, we extracted the data when the displacement of the tail end of the actuator in vertical direction is zero. Thus we obtained the relationship between the air pressure and the force on the tip of the actuator. As shown in Fig. 10, the comparison of the simulation and the experimental results showed similar trend and relatively small error, which indicated the reliability of the FEA simulation.

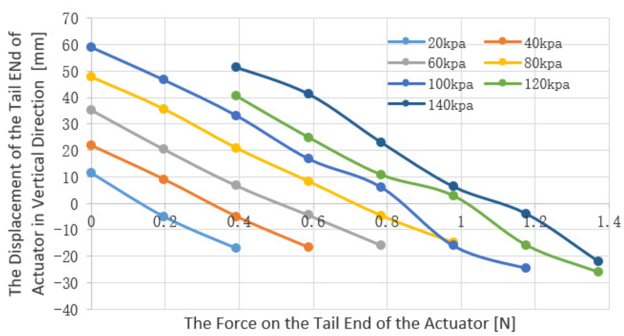

Fig.9. The relationship between the force on the tail end of the actuator and the displacement of the tail end of the actuator in vertical direction.

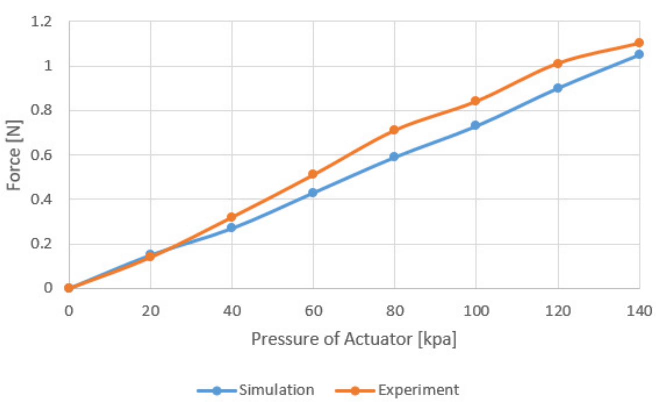

Fig.10. Comparison of the simulation and the experimental results

B. *The Performance of the Force Feedback of Index Finger*

As shown in Fig. 11, we install a force sensor (Honeywell FSG15N1A) between the finger tip and the mechanism, and thus we can measure the force with different air pressure and in different configuration of the fingers.

The performance under three configurations was measured. The configuration 1 is defined when $\theta_1=\theta_2=\theta_3=0°$, the configuration 2 is when $\theta_1=\theta_2=45°$, $\theta_3=0°$, and the configuration 3 is when $\theta_1=\theta_2=60°$, $\theta_3=0°$. The angles are shown in Fig.3.

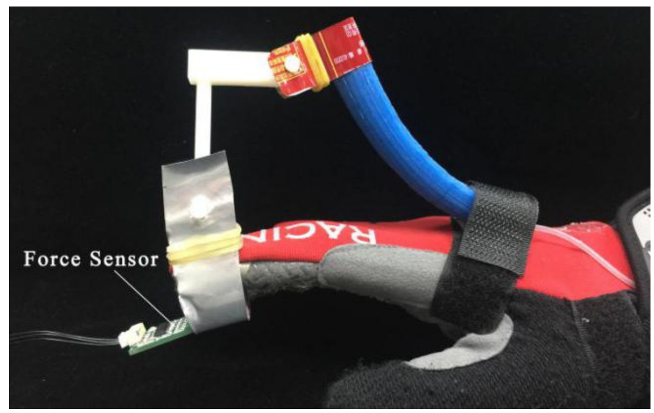

Fig. 11. Illustration of platform for measuring the performance of the glove

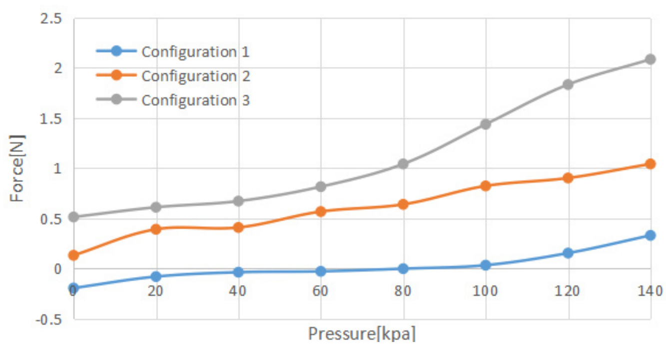

Fig.12. The force on fingertip with different air pressures in the three configurations.

As shown in Fig.12, the feedback force on the fingertip can be modulated by the air pressure. For each of the three configurations, the feedback force changes continuously along with the increase of the air pressure.

For the free space simulation (i.e., the air pressure is zero), the resistance force in all the three configurations are less than 0.58N. For the constrained space simulation (i.e., the air pressure is larger than zero), the maximum feedback force in the third configuration is 2.1N.

C. *Compared to Other Force Feedback Gloves*

The glove is 30.8g per finger, so even installing with soft actuators and mechanisms on all five fingers, the glove's weight is about 150g. This small weight means that the glove is suitable to wear for a long time without causing fatigue. As shown in Table 2, the proposed glove using soft actuators is much lighter than CyberGrasp, and provides a large range of motion. It could provide active force and variable stiffness.

The soft actuators and the mechanism are all mounted in the dorsal-side, so the motion range of the fingers would not be constrained by the glove. In both free and constrained space, the glove can support full hand opening and closing.

The proposed solution can ensure the safety of the user even at higher pressures. Compared with the rigid rod, the actuator is the bottle neck. In the case of uncontrollable higher pressures, the only possible failure is that the actuator might be damaged and the air will be leaked from the actuator.

D. Discussions

Experimental results validate that the proposed solution can meet the demand of both the free and constrained space simulation. However, rigorous work needs to be performed to achieve a high performance force feedback glove.

First of all, one major limitation of the proposed physical prototype is that we could not accurately control the magnitude of the normal force perpendicular to the users' fingertip. In virtual reality scenarios, the force perpendicular to the fingertip is important for simulating the grasping of virtual objects. As shown in Fig. 1, the normal force F_p is changing and dependent on the angle θ_4.

In order to accurately produce an expected normal force on the fingertip, several steps need to be carried out. First, we first need to mount a sensor on the hand and thus to measure the angles of the joints in real-time. Second, we need to produce an accurate force F_1 along the line $\overline{EF}$. As there exist transmission error of the linkage mechanism, along with the actuation error of the electro-pneumatic regulator and pump, the open loop control using the Eqn. (7) may introduce error for the force F_1. One possible solution is to introduce a force sensor to formulate a closed-loop control system, and thus to compensate the error by adjusting the pressure inflated into the soft actuator in real-time.

Secondly, the normal force provided for simulating constrained space sensation is not large enough. The reason is that the normal force may become small when the angle θ_4 becomes large along with the rotation of the finger. In order to enlarge the normal force, the linkage mechanism needs to be optimized to increase the normal force component.

Thirdly, the proposed solution is not adaptive to different users. New mechanism needs to be proposed for adapting to the hand size of different users.

Last but not the least, finger tracking is needed. Only after integrating position sensing and force feedback, we can simulate virtual objects with varied stiffness.

V. Conclusion and Future Work

In this paper, we introduce a light-weighted force feedback glove using pneumatic-driven soft actuators. By integrating a soft actuator and a simple linkage mechanism, the glove can allow free motion of fingers for simulating free space sensation, as well as provide resistance forces on fingertip for simulating constrained space sensation.

The glove is light-weighted with about 30g for both the actuator and the mechanism on each finger. In free space, the friction force is 0.58N, while in constrained space the glove could provide 2.1N force feedback on the index fingertip in specific hand configurations. The length and the diameter of the air tube directly influence the responsiveness of the force feedback glove. With a larger diameter and a shorter length, the responsiveness of the air tube would be faster. It is an important topic to study the quantified impact of the diameter and the length of the tube on the responsiveness of the force feedback glove.

In the future, we plan to extend to all five fingers with finger position feedback and distributed tactile sensing on the palm. Furthermore, we plan to combine the glove with head-mounted displays to enable users experience the haptic sensation of grasping soft objects.

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