3D-Printed Modified Pinch Valve for Controlling Pneumatic Artificial Muscles

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***Abstract*- Soft robotics is a rapidly growing fields in the past decade. Despite its compliant nature and low weight, which is suitable for human interaction applications, still suffering from the low-speed actuation compared to the rigid actuators. In this paper, a 3D printed modified pinch valve is presented to control a pneumatic artificial muscle. This valve can provide high flow rate which can increase the pneumatic muscles actuation speed. 3D printed artificial muscle is used to validate the controllability of the valve. The muscle frequency increased from 0.1 Hz to reach 3.5 Hz. A chain of five muscles is controlled and reach 1.5 Hz.**

Keywords— Soft robots, valves, soft wearable robots.

I. INTRODUCTION

Soft robotics is one of the rapidly growing fields in the past decade [1]. The main advantage of soft actuators is their compliant nature making it suitable for human interaction applications. Soft wearable robots are used to provide more safe, comfortable, and low weight rehabilitation and assistive devices [2].

Different pneumatic soft actuator designs are used in rehabilitation and assisting devices such as Pneumatic Artificial Muscles (PAMs) [3], [4], gel muscle [5], Bubble Artificial Muscles (BAMs) [6]–[8] and fabric-based actuators[9]–[12]. These pneumatic actuators provide more comfortable and lower weight solution for the rehabilitation applications than the rigid actuators, however, traditional electric actuator is still the choice of most knee assistive devices because of the higher accuracy and efficiency [13].

The dynamic behaviour of the pneumatic soft actuators depends on the actuator design and the pneumatic supply system [1]. The higher actuator volume causes increase in the rise time and consumes more air during actuation. The pneumatic supply system components including the valves are usually choosen from off the shelf components [14], [15]. The flow rate limit of the valves can limit the inflation and deflation speed of the soft actuator specially with the high volume actuators.

There are various pneumatic kits designed for controlling soft actuators using commercial valves. Soft robotic tool kit, which is one of the earlies pneumatic controllers designed for controlling soft actuators, suggested using SMC VQ100 valve that can provide 5 SLPM/bar flow rate [16]. A Wireless Compact Control Unit (WiCCU) is used to control soft colonoscope using Parker VSO LowPro miniature proportional valve that has a flow rate of 8.3 SLPM/bar [17], [18]. FlowIO is a pneumatic modular platform designed for controlling soft wearable robot using SMC S070 valve which is suitable for low volume soft actuators as its flow rate limited to 2.5 SLPM/bar [19]. Another disk top platform is used for real-time control applications of pneumatic soft robots contains Festo VEAB proportional pressure regulator that can provide about

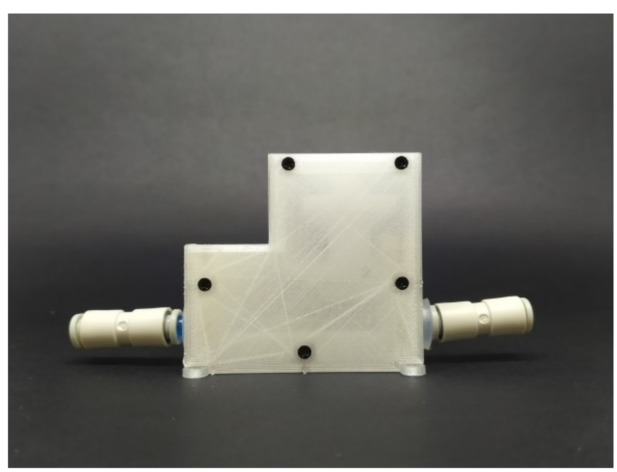

Figure 1. 3D printed soft-rigid valve (MPV).

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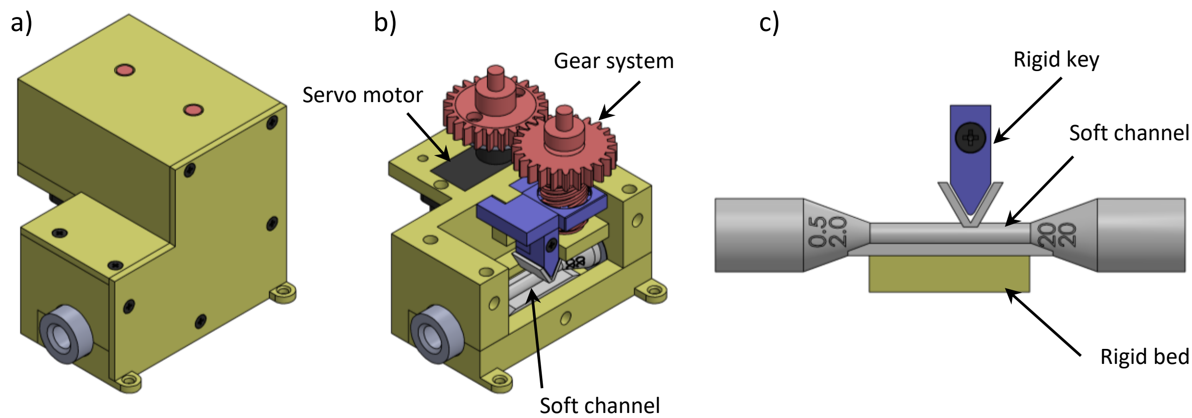

Figure 2. 3D model of the MPV, a) assembly model of the valve, b) Uncovered model of the valve, c) front view of the soft channel, rigid key, and rigid bed.

20 SLPM/bar [20].

In this paper, 3D-printed modified pinch valve (MPV) is presented for controlling pneumatic soft actuators, shown in Fig. 1. The valve internal tube is 3D printed that giving the ability to module the design depends on the required output flow rate. The tube is fixed from the top and the bottom to enhance the valve dynamic response compared to conventional pinch valve. The valve can provide up to 47 SLPM/bar flow rate because of the internal diameter of the soft channel, which is higher than most of the previous pneumatic kits for soft robots. 3D printed GRACE muscle [21] is used to validate the valve performance and the results shows increasing the frequency of the muscle from 0.1 to reach 3 Hz in a single muscle control and the frequency reach 1.5 Hz in five muscle control configuration which indicate increasing in the actuation speed of the muscle.

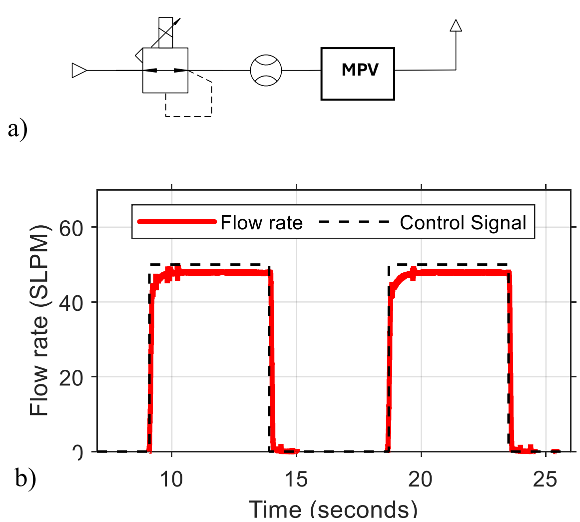

Figure 3. The dynamic performance test setup and results of the MPV, a) dynamic test pneumatic setup, b) the output flow rate of the MPV with square wave input.

II. Methodology

A. MPV design concept, fabrication, and characterization

The MPV is a 3D-printed modified design of the pinch valve used to control a soft actuator through changing the inlet and outlet air flow rate. The design concept of the MPV is based on the pinching a soft channel which the air flow passes through. Resulting in reducing the internal area of the tube, reduce the air flow rate.

The MPV consists of a soft channel, rigid key and power transmission system actuated by servo motor, as shown in Fig. 2. The servo motor is used to control the rigid key position through a gear system and power screw that converts the rotational motion to linear motion. The rigid key is fixed in the soft channel to constrain the height of the soft channel during control process. Also, the soft channel is fixed from the bottom side in the rigid bed to prevent any unrequired motion by the soft channel as shown in Fig. 2(c).

The soft channel is designed with input-output diameter equal to the pneumatic tubing 6 mm. The middle of it has a smaller diameter, chosen to be 2 mm, which limit the maximum flow rate of the source. An additional soft plate is added in the bottom to prevent direct contact between the channel and the rigid bed during pressing which can cause channel cutting. A V-shape part is added in the upper side of

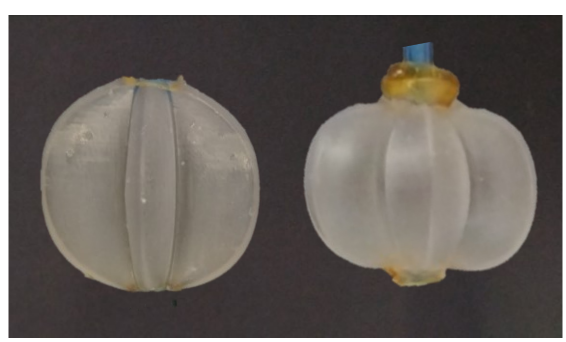

Figure 4. 3D printed GRACE muscle in the deflated and inflated configurations.

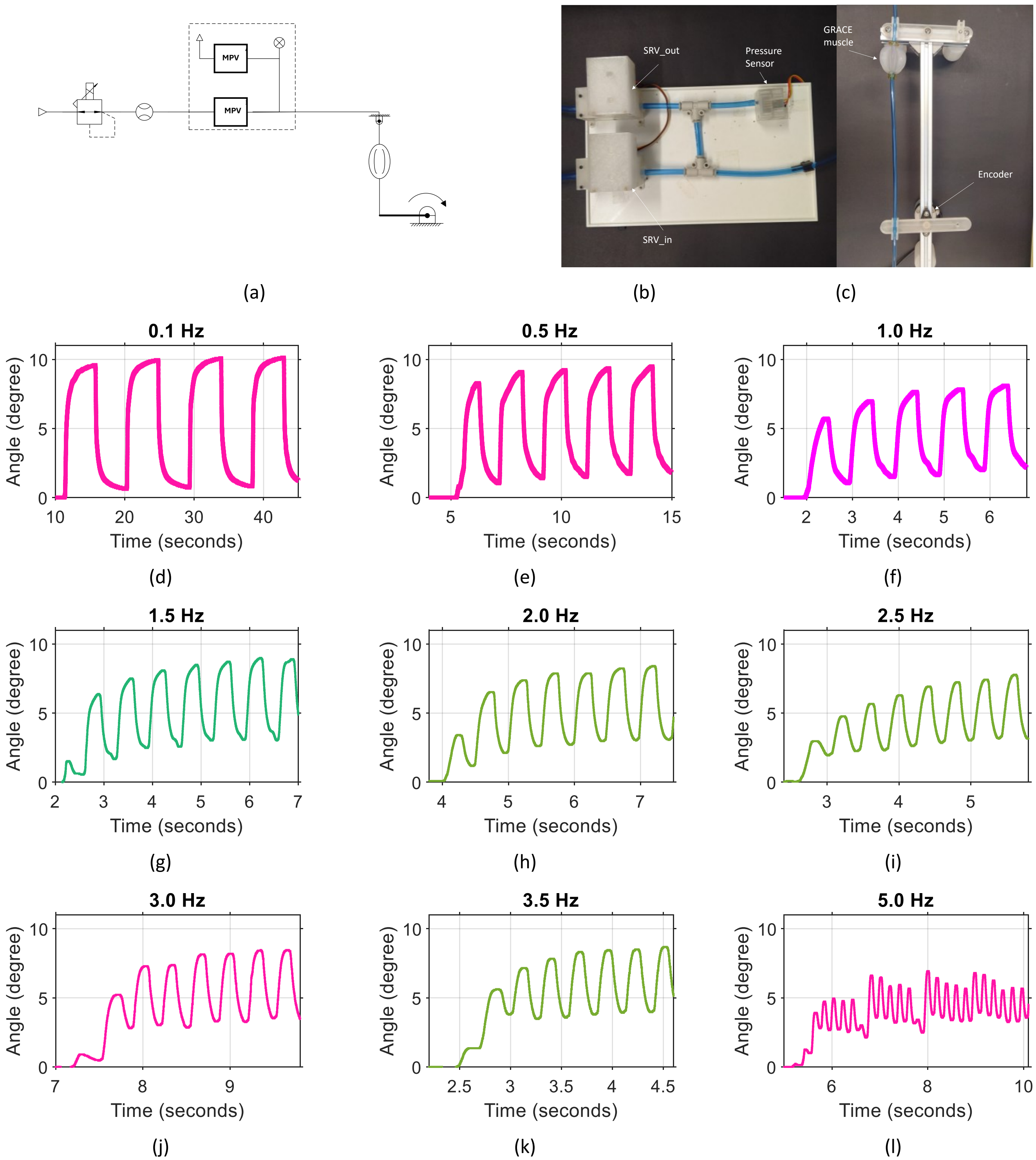

Figure 5. Control of GRACE muscle Using MPV pneumatic kit, a) Scheme of the pneumatic circuit of the control experiment, b) MPV pneumatic control kit for soft actuators contains two MPV s and pressure sensor, c) GRACE muscle connected to link with encoder, d) experiment results with different frequencies.

the channel for gluing the rigid key on it. The soft channel is fabricated using Formlabs 3D printer by Formlabs 80A flexible resin with wall thickness of 0.5 mm. The remaining parts of the MPV, the rigid key, power transmission system, and body, are printed using Ultimaker S5 3D printer by PLA material.

The dynamic response of MPV with soft channel has internal diameter 2 mm is measured using the pneumatic setup shown in Fig. 3. It consists of a compressor, pressure regulator (ITV2050, SMC) to fix the input pressure to the valve to 100 kPa and flow sensor (HAFUHT0050L4A, Honeywell). The MPV is controlled using a function generator and Arduino to control the servo motor. The control signal is square wave with frequency 0.1Hz. The output flow rate reaches 40 SLPM in 0.2 sec and 47 in 1.0 sec in the opening. In the closing it reaches

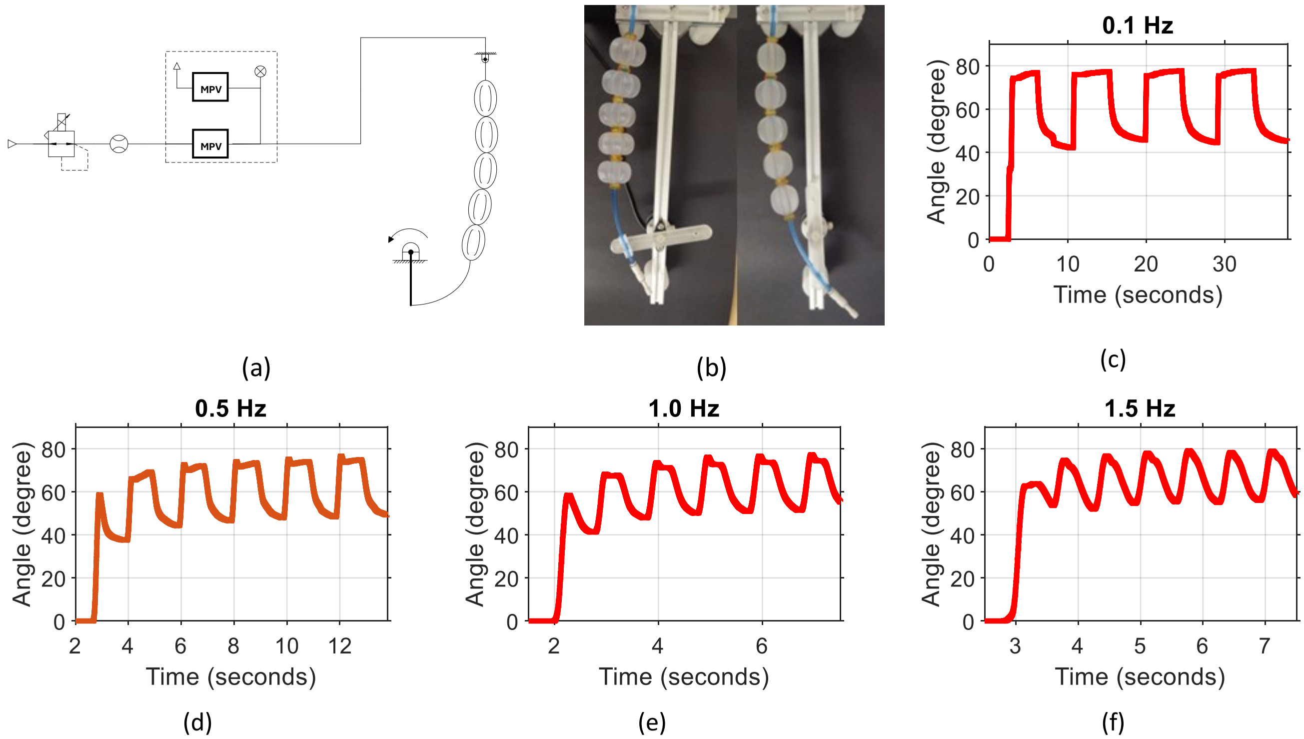

Figure 6. Control Experiment of chain of GRACE muscles using MPV pneumatic control kit, a) scheme of the experiment pneumatic circuit, b) The GRACE chain in pressurized and depressurized mode, c) Experiment results with different frequencies.

0.5 SLPM in 0.2 sec and 0 SLPM in about 0.5 sec, as shown in the Fig. 3.

B. *Control GRACE muscle using MPVs*

The GRACE muscle is a type of the Pneumatic Artificial Muscles (PAMs) that fabricated with one monolithic element, resulting muscle that can be directly 3D printed, as shown in Fig. 4 [21]. The design implements contraction and elongation through controlling the pressure without need to external constants. This muscle can be fabricated with different materials and different sizes to achieve the required motion. The fabricated muscle is a contraction model, which can reach contraction ratio of 25% when it pressurized to 26 kPa. This muscle is fabricated with Formlabs 80A flexible material with height of 40 mm.

The MPV pneumatic control kit, shown in Fig. 5(a, b), consists of two MPVs with pressure sensor (ASDXACX100PGAA5, Honeywell), which is used to control the pressure inside a 3D printed GRACE artificial muscle as shown in the Fig. 5(b). A proportional controller is used to control the pressure using pressure sensor feedback. A pressure regulator is used to maintain the source pressure at 100 kPa and the flow sensor is used to measure the maximum flow rate input to muscle during muscle control. The muscle is connected to rotational link with incremental encoder to detect the muscle contraction, as shown in Fig. 5.c.

Firstly, the MPVs are used to control the pressure in the GRACE muscle with 0.1 Hz square wave between 0 and 26 kPa with measured rotational angle. The results show change in the angle between 1 and 10 degrees and the maximum flow rate during the muscle control reach about 8 SLPM. Then, higher frequencies are used to validate the effect of using the MPV kit in the muscle frequency. The results, shown in Fig. 5(d-l), present the joint angle response to frequencies from 0.1 to 5 Hz.

C. *Control Chain of GRACE muscles in knee flexion mechanism using MPVs*

A chain of five GRACE muscles is used in a mechanism shown in Fig. 6. The mechanism is used to validate valve ability to control high volume actuators with the required frequencies. The mechanism connected to chain of the GRACE muscles that increase the required air volume for actuation. The chain of muscles reached frequency of 1.5 Hz. The MPVs are used to control the muscle chain to achieve 1.5 Hz with amplitude about 20° in the mechanism joint, as shown in Fig. 6(c-f).

III. Results Discussion

The MPV is designed to provide high flow rate to control the soft robots with high volume. The valve can provide up to 43 SLPM/bar, as shown in Fig. 3, which is higher than most of the pneumatic valves that used to control pneumatic soft actuators. The valve can reach the maximum flow rate in about 0.3 seconds that it is suitable to the soft actuators dynamics.

Two MPVs are integrated in pneumatic kit with pressure sensor and controller to be used to control the pressure inside the pneumatic soft actuators, as shown in Fig. 5(b). additional to the high flow rate ability of the valve, which is useful with controlling the high-volume actuators. Using proportional controller with separated gains for each valve is another advantage in controlling the GRACE muscle over the industrial pressure regulators. In the previous work, the GRACE muscle with the same length can reach maximum amplitude with frequencies up to 0.1 Hz using pressure regulator[21]. The muscle can reach the maximum contraction but oscillate around the maximum contraction position with the frequencies higher than 0.1 Hz. The reason for the limitations in performance is the pneumatic control circuit, primarily the pressure regulator. To solve this problem, a separated gains are used for each of the inlet valve and the outlet valve. This gives the ability of increasing the outlet gain to the inlet gain to equalize the inflation to deflation speed, resulting higher operating frequency.

The high output flow rate is another advantage of the MPVs that utilized to control a chain of GRACE muscles. Fig. 5 show the changing in the amplitude of motion of the chain with changing the desired frequency. The angle amplitude is nearly similar in frequencies 0.5, 1.0 and 1.5 Hz.

IV. Conclusion

This paper presents a 3D printed MPV valve to be used to control pneumatic soft artificial muscles. The valve can provide a high output flow rate to reach 47 SLPM, which is required to control high volume pneumatic muscle. A 3D printed GRACE muscle is used to validate the valve control kit. The muscle is controlled with higher frequency than the previous work reaches 3.5 Hz [21]. Chain of muscles is used to validate the valve high flow rate and it can reach 1.5 Hz.

In the future work, another 3D printed technologies that print multi-material will be investigated to directly print the valve in one print. The valve dimensions will be optimized to increase the portability to be suitable for the wearable devices. Additional flow rate feed-back will be added to the controller to enhance the muscle response.

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