Soft Passive Valves for Serial Actuation in a Soft Hydraulic Robotic Catheter[1]

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1 Background

Joseph L. McKibben devised soft robotic actuators in the 1950s when he developed arm orthotics for his daughter who suffered from poliomyelitis [1]. The resulting McKibben actuator consists of an elastomeric tube encased by a mesh of equal and opposite fiber orientations allowing for axial expansion or contraction. Recent research of fiber-reinforced enclosed elastomers (FREEs) has focused on varying wrap angles to produce twisting, bending, spiral, and screw motions [2]. Using the FREE model, we propose a soft robot that can locomote through human vasculature as shown in Fig. 1. The robot will be powered by a single hydraulic line connected to a saline pump, and the robot will be comprised of two parts: a locomotion section and an orientation section, much like typical robotics arms. The locomotion section will move through human vasculature with two spiral sections and an extender in the sequences shown in Fig. 2. The orientation section will contain two degrees-of-freedom allowing for a theranostic tip to sense its surroundings and perform procedures. To create these two sections and link the actuators together, new valves must be created which allow for sequential actuation of the locomotion segments with a single pressure line (Fig. 2). These cracking pressure valves must be tunable and have asymmetric hydraulic resistances.

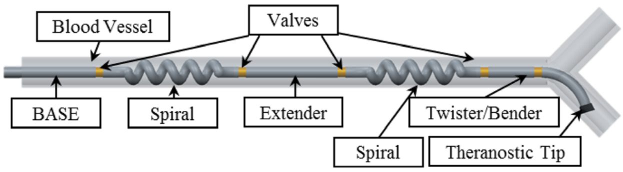

Fig. 1 Catheter robot traversing a blood vessel

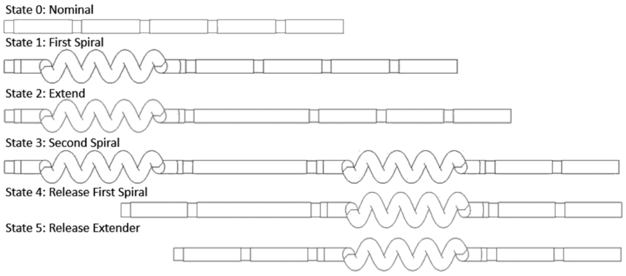

Fig. 2 Actuation states of catheter robot segments

Although much research has been performed in soft robotics, less attention has been paid to the hydraulic valves used. Napp et al. have developed a passive bandpass valve that consists of two moving diaphragms [3]. Unlike previous works, our valve consists of a single diaphragm. The valve acts like a two-way check valve. Low-pressure differentials are blocked out while pressures above the cracking pressure are able to flow through the valve wall, allowing each segment to fill up to a desired pressure. This paper contributes a design of asymmetrical cracking pressure valves with an empirical design table in an aim to achieve the intravascular locomotion proposed in Fig. 2. The design is scalable to catheter dimensions and magnetic resonance imaging (MRI) compatible.

2 Methods

The design draws inspiration from the mitral valve which consists of three flaps which form a cone. To create bidirectionality, the flaps were removed allowing the cone to invert on itself. The inversion of the cone created asymmetric cracking pressures which was the desired design parameters. The cracking pressure was defined as the pressure that first generated noticeable flow through the valve. This was determined manually by measuring the pressure when water first cracked through the valve. The valves created in Fig. 3 show the design and flow path for the forward and reverse flow directions.

The valves were created through a silicone molding process. A two-part mold was 3D printed (Objet260 Connex, Stratasys, Inc., Eden Prairie, MN), which contained six varying cone angles from 0 deg to 50 deg as shown in Fig. 4. A 3/8 in. diameter bushing with a 3/8-16 UNC hole was placed into the mold and served as the outer casing for the silicone valve. To mold the valve within the body, 8A durometer silicone (TAP Platinum Silicone, TAP Plastics, San Leandro, CA) was injected into each valve casing and the mold was degassed. The top-half of the mold was placed and a set of adjustable parallels was used to set the thickness of the valves.

An empirical study was performed to test the bidirectional cracking pressure of the soft valves in both the forward and reverse directions. The valve thickness and cone angle ranged from 0.025 in. to 0.100 in. and 0 deg to 50 deg, respectively. To test the cracking pressure of each valve, the pressure of the

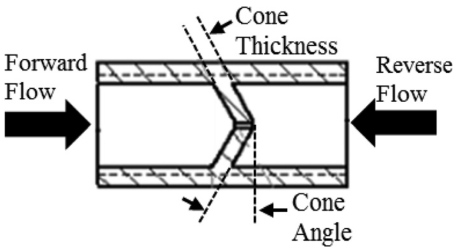

Fig. 3 Valve diagram showing the thickness and angle of the valve as well as the forward and reverse flow directions

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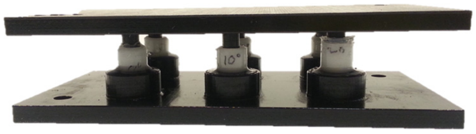

Fig. 4 Two-piece mold with six varying cone angles and a variable height

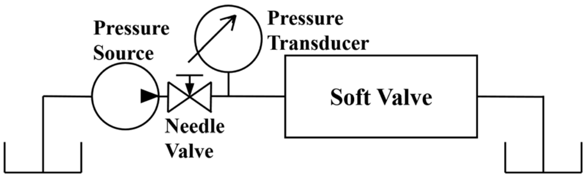

Fig. 5 Hydraulic pump setup

Table 1 Results of valve experiment (pressures in psi)

	Valve thickness							
	0.050 in.		0.075 in.		0.100 in.		0.110 in.	
Angle (deg)	P_{fwd}	P_{rev}	P_{fwd}	$P_{\mathbf{rev}}$	P_{fwd}	P_{rev}	P_{fwd}	P_{rev}
0	3.0	3.0	7.3	7.3	12.6	12.6	15.0	15.0
10	3.0	5.8	5.2	9.8	10.6	15.5	12.3	15.6
20	3.1	5.3	7.6	12.1	8.6	16.5	11.5	17.5
30	2.7	5.6	2.4	11.3	7.1	17.8	9.3	19.8
40	2.4	5.3	2.6	12.8	4.1	17.8	7.0	20.1
50	2.8	4.9	2.5	6.8	4.0	17.9	6.4	20.8

hydraulic source was gradually increased. The pressure that first cracked the valve, resulting in flow, was recorded based on the reading from a pressure transducer (MLH100PGL06A, Honeywell International, Inc., Morris Plains, NJ). The test setup, as shown in Fig. 5, consisted of a pressure source connected to a needle valve to control the input pressure, as well as a pressure transducer used to measure the pressure applied to the soft valve using a microcontroller (Arduino Nano, Arduino LLC, Cambridge, MA) sampling at 500 Hz.

3 Results

The results of the bidirectional cracking pressure analysis are shown in Table 1. The P_{fwd} box is the cracking pressure in the forward direction and P_{rev} is the cracking pressure in the reverse direction both reported in psi. Figure 6 shows the normalized cracking ratio which was found by $P_{\mathrm{rev}}/P_{fwd} - 1$.

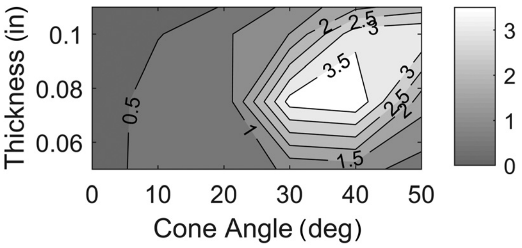

Fig. 6 Contour of the cracking pressure ratios ($P_{\mathrm{rev}}/P_{fwd} - 1$) for varying thicknesses and cone angles

4 Interpretation

Table 1 shows that varying the cone angle and valve thickness substantially changes the bidirectional cracking pressure. Thicker valves resulted in higher cracking pressures. Steeper cone angles resulted in a lower forward cracking pressure and a higher reverse cracking pressure. The normalized cracking ratio in Fig. 6 shows a saddle where the cracking pressure ratio varies from 3.5 (35 deg, 0.075 in.) to less than 0.5 (0 deg, 0.1 in.). The valve design created through this process has the potential to achieve the locomotion in Fig. 2 through the utilization of asymmetric cracking pressures.

The tests were subject to several sources of error, mainly in the recording of the cracking pressure since a manual detection of initial flow through the valve was used. Additionally, various valves cracked with varying flow rates, which made it difficult to obtain a true and definite cracking pressure. The normalized cracking ratio was developed to reduce the error in the cracking pressure method by examining the relationship between the forward and reverse cracking pressures for each valve. The results provide a promising design approach that could be scalable for soft actuator valves.

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