Development of a Peristaltic Endoscope

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Abstract

A device that could locomote through curving and tortuous spaces would find many applications in medicine and in industry. Invertebrates such as earthworms and leeches can solve this problem using peristaltic locomotion. We describe a device consisting of three braided pneumatic actuators in series that can successfully locomote peristaltically. The device can locomote forwards and backwards in elevated and curving tubes, and with a plastic sheath around it.

1. Introduction

A device that could pull itself through small tubes and could bend itself around curves would have many applications. For example, it could be used to maintain and repair machines with complex internal plumbing. Perhaps more importantly, it could be used for endoscopy and catheterization within the human body. Currently, endoscopes are either semi-rigid or completely rigid tubes that can only be inserted with the exertion of considerable force by a physician. As a consequence, they are liable to damage the internal vessels of the body, and may also induce patient discomfort during insertion. Even catheters, which are more flexible, can do damage when pushed into the different vessels and lumens of the body [1-4]. At the same time, it is becoming clear that regular endoscopic examination of internal structures can be essential for early diagnosis of disease [5].

Biological organisms such as slugs, leeches and earthworms, can readily insert themselves into and move through curving, tortuous spaces [6]. In general, they do so by using a hydrostatic skeleton [7-9]. This consists of a fluid-filled lumen surrounded by circumferential and longitudinal muscles. Contraction of the longitudinal muscles allows body segments to shorten longitudinally and expand radially; conversely, contraction of the circumferential muscles allows body segments to lengthen longitudinally and contract radially. Appropriate coordination of the movements of different segments results in peristaltic locomotion. Because their body is flexible, these organisms can readily conform to curving and tapering spaces. In addition, local reflexes allow these organisms to retract their bodies in response to obstacles and to noxious stimuli, as well to seek out food and light.

In recent years, there have been several attempts to use biological inspiration as the basis for novel endoscopes. Several investigators, inspired by the flexible movements of snakes, have created endoscopes that can bend in response to the activation of shape memory alloy wires [10, 11]. More recently, two groups have described a prototype of an autonomous device that can use localized vacuum to anchor to the colon wall and a bellows-like expansion and contraction to move itself through tubes and excised portions of porcine intestine [12, 13]. Another group has described a prototype endoscope that is analogous to an earthworm, consisting of balloon-like gripper devices that expand radially to grip the lumen wall which are interdigitated with extensor segments that can expand or contract [14].

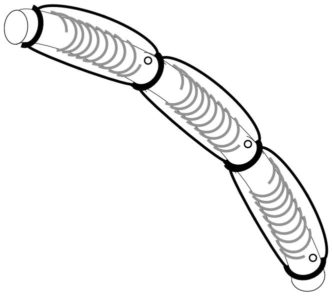

Figure 1. Schematic diagram of three actuators in series.

A major obstacle to the development of peristaltic devices has been the difficulty of finding actuators with appropriate muscle-like properties. Recent improvments in the McKibben braided pneumatic actuator [15-19] have made it possible to miniaturize this device and operate it using relatively low pressures. McKibben Artificial Muscles were invented by Gaylord [20] and are also known as Rubbertuators [21] or braided pneumatic actuators [15, 22]. The basic design consists of a bladder surrounded by a mesh. When the bladder is inflated, the mesh expands radially, but contracts along its length. The contraction produces a force in tension.

We report that it is possible to construct a series of McKibben-like actuators around a central hollow tube (see Figure 1), and to activate them in sequences that allow them to generate peristaltic locomotion within curving tubes. Each actuator is provided with its own source of compressed air, and a spring is placed within each actuator to provide a restoring force once air pressure is removed.

2. Theory of Operation

McKibben artificial muscles consist of an expandable bladder inside a tubular mesh made of relatively inelastic fibers [16, 17]. When the bladder is inflated, the only way for the volume of the bladder to increase is for the diameter of the mesh to increase. The inextensible fibers of the mesh can only do this by simultaneously moving outwards in a radial direction and moving inwards in the axial direction, thus converting circumferential pressure forces into an axial contraction force. Ordinarily, deflating these actuators allows the fibers to return to their resting position, lengthening the actuator. Building the actuator around a central hollow lumen introduces friction that resists the tendency of the actuator to re-lengthen once it is no longer inflated. For our application, therefore, we insert a spring within the actuator around the lumen to provide a restoring force.

In order to create the ability to differentially contract and expand different actuators, it is necessary to place more than one in series. If the individual actuator length at rest is L_r, and the length when contracted is L_c, then the contraction distance for an individual actuator, or (L_r-L_c), is equal to ΔL. Thus, in one motion cycle, the robot can theoretically move a distance of $3\Delta L$.

The sequence of activation for peristaltic locomotion is to first inflate actuators from front to back, then deflate them in the same order (see Figure 2).

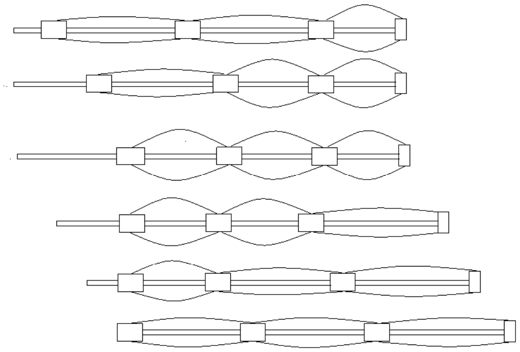

Figure 2. **Sequential activation of actuators for peristaltic locomotion.**

3. Materials and Methods

Materials: Clear PVC tubing was chosen for the inner lumen of the device because of its flexibility, its relatively low coefficient of friction, and its ability to bond with cyanoacrylate. Tubing of outer diameter 0.25 inches and inner diameter of 0.175 inches was used.

Each actuator is supplied with air via small medical grade polyethylene tubes (Intramedic Clay Adams PE200, inner diameter .055 inches, outer diameter .075 inches, Fisher Scientific Corp.), which were chosen because, during construction, they must be semi-rigid to be properly placed and must have a low coefficient of friction to allow them to slide past one another. Polyethylene also bonds well with cyanoacrylate, allowing for a rigid seal with the PVC lumen.

The front of the device consists of a fixed head piece machined out of aluminum (a cylinder of diameter 0.5 inches with a central circular peg (diameter 0.185 inches) that fits within the PVC tube. Aluminum was chosen because it is lightweight, is easy to machine and makes a good press fit in the inner lumen.

In order to allow the actuators to slide freely over the central tube, bearings were placed between each actuator. In addition, the bearings were connected to one another to provide a ledge both for the moving seal (described below) and the restoring force spring. The bearings are a composite of three thermoplastic bearings (B17-13: 5/16 inch inner diameter, 3/8 inch outer diameter, 3/4 inch length; B17-16: 3/8 inch inner diameter, 15/32 inch outer diameter, 1/2 inch length; W. M. Berg Inc., East Rockaway, N. Y.). Two of the bearings are in series with one another and the third bearing is slipped over the two smaller bearings and glued in place over the joint of the two inner bearings (Figure 3).

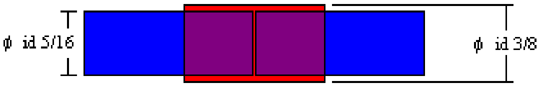

Figure 3. **Schematic of bearings.**

The restoring force spring is constructed by soldering together two copper-beryllium springs (outer diameter 0.408 inches, length 1.75 inches, wire diameter 0.0254 inches, spring rate 0.528 lbs/inch, U-CS-41, Small Parts Inc., Miami Lakes, FL) to make a spring whose total length is 3.5 inches.

To create an airtight chamber around the central tube, two kinds of seals were found to be necessary. An inner seal, which is movable, seals the ledge of the bearing (Figure 4) to the inner lumen. An outer seal acts to seal the inner surface of the bladder to the shelf of the bearing (Figure 4). The seals and bladder are constructed of latex, because of its elastic properties. If the seals are pulled, the latex will stretch as opposed to tearing.

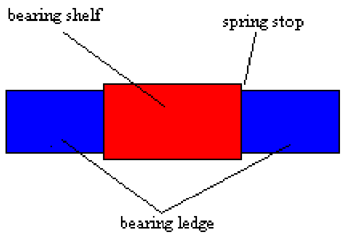

Figure 4. Key locations on the bearing.

The movable seal is a cylindrical segment of medical grade latex tubing (0.375 inch diameter) attached with cyanoacrylate glue to the PVC tube, and attached with a toluene and petroleum distillate glue (Plumber's Goop, Eclectic Products, Inc.) to the ledge of the bearing. The bearing can move over the PVC tube while maintaining an airtight seal because the latex tube bends over itself (see Figure 5).

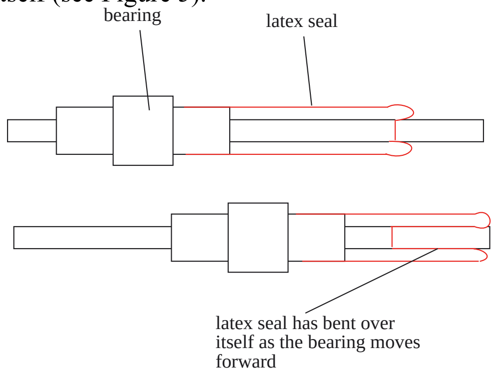

Figure 5. Schematic of moving latex seal.

Covering the bladder is a mesh. The mesh is a tubular braiding of nylon wires (inner diameter 0.5 inches, Clean Cut, Techflex Inc., Sparta, N. J.). Since nylon is inelastic, the actuator is isovolumetric. When the actuator is stretched in the radial direction by inflation, it contracts along its length.

Construction: Three small holes are drilled in the PVC along its length for the installation of the air lines (approximately 3/32 inch diameter). The first hole is 0.5 inches from the head piece, the second hole is 5 inches behind the first, and the third hole is 4.5 inches behind the second. The most anterior air line is pushed through the lumen of the PVC tube and its end is then pushed through the most anterior hole. It is then glued to the PVC tube using cyanoacrylate adhesive (MM M-line accessories, M-Bond 200 adhesive). The movable latex seal (1-a, Figure 6) is affixed to the PVC tube with cyanoacrylate adhesive and bearing 1 is slipped onto the PVC tube from the rear.

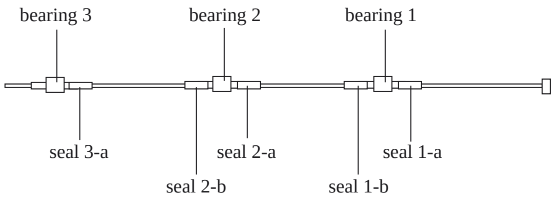

Figure 6. Actuator components.

The latex seal is folded over itself and placed around the bearing ledge. It is sealed onto the bearing with Plumber's Goop. The restoring force spring is inserted around the PVC tube from the front. It is fit over the movable latex seal and the end of the spring rests against the spring stop (Figure 4). The spring is secured there using cyanoacrylate adhesive. After the spring is in place, the end-cap is inserted into the PVC tube and sealed in place with Plumber's Goop. After all the joint seals have been given adequate time to dry (approximately 12 hours), the outer latex bladder is put into place, but not yet sealed. Movable latex seal 1-b is affixed to the PVC tube and bearing 1. The second air line is now installed. Movable seal 2-a is affixed to the PVC tube, but not yet sealed to the bearing. The second spring is now slid over seals 2-a and the fully installed 1-b. It is pulled forward slightly to accommodate the installation of bearing 2. Seal 2-a is now sealed to the bearing and spring 2 is affixed. The second bladder is now placed over the skeleton of the second actuator. This process is repeated for the third actuator. Once all of the actuators are built, the outer latex bladders are sealed onto the bearing shelves and the nylon mesh is slid over the device. The mesh is secured at each actuator intersection by tightly wrapped electrical tape. It is further secured by coating the tape with another adhesive (Wall Covering Border and Repair Adhesive, Dynamic, Inc.). A schematic diagram of a complete single actuator is shown in Figure 7.

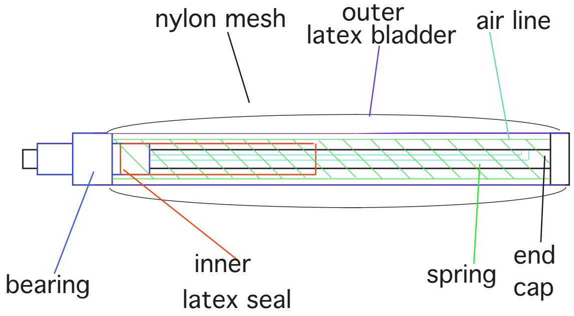

Figure 7. Schematic diagram of single actuator

Control: In order to generate peristaltic locomotion, the actuators needed to be inflated in the sequence shown schematically in Figure 2. The three air lines for each of the actuators were attached to two 8-way solenoid values. One valve served as an inlet and the other functioned as an exhaust. Only three of the ports on each valve were used, one for each actuator. The valves were controlled using code that turned them completely on for 0.6 seconds at a pressure of 40 psi, and then turned them completely off for 0.4 seconds. The sequence of control pulses to actuators 1, 2 and 3 over the time of the cycle is illustrated in Table 1. Each entry represents the status of the valve; a "+" indicates that it is fully open, and a "-" indicates that it is fully closed.

	1	2	3
0.2 s	+	-	-
0.4 s	+	+	-
0.6 s	+	+	+
0.8 s	-	+	+
1.0 s	-	-	+

Table 1

Backwards locomotion was achieved by reversing the order of activations (i.e., switching columns 1 and 3 of Table 1).

4. Results

The robot successfully locomoted forwards and backwards through a transparent acrylic tube (1 inch outer diameter, 0.75 inches inner diameter, 8565K38, McMaster Carr, Cleveland, OH), which was either horizontal or held at a 15° incline (Figures 8 and 9).

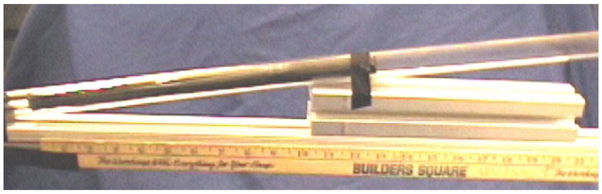

Figure 8. Start of locomotion in elevated tube.

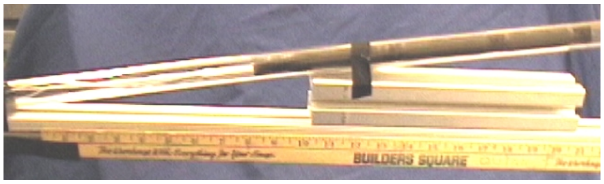

Figure 9. End of locomotion in elevated tube.

The maximum theoretical velocity of the robot was $3\Delta L$, as defined above, divided by the time for a single cycle, which was 1 second. The resting length of a single actuator is 4.75 inches, and its fully contracted length is 4.375 inches, so that ΔL is .375 inches. Thus, the predicted maximum velocity is 1.125 in/ sec. When the robot did not have to pull more than the weight of its air tubes (see left side of Figure 9, within the acrylic tube), the average velocity in two trials was 0.2 in/sec, so that the robot's locomotion efficiency was 17.8%.

The robot could also locomote forwards and backwards through an elevated curving translucent polyethylene tube (0.875 inches outer diameter, 0.75 inches inner diameter, 5181K93, McMaster Carr Inc.; Figures 10 and 11).

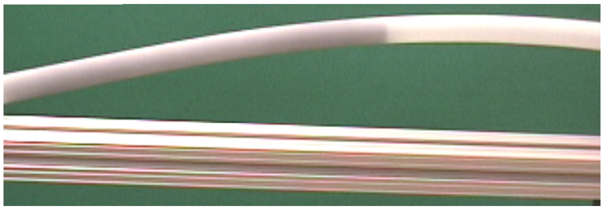

Figure 10. Start of locomotion in elevated, curved tube.

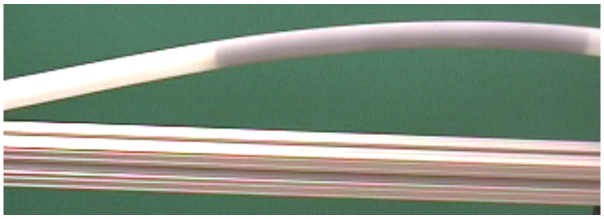

Figure 11. End of locomotion in elevated, curved tube.

If the robot were to be used in clinical applications, it might be important to cover it with a sterilizable, disposable membrane. We tested the ability of the robot to locomote when covered entirely with a thin plastic sheet (Saran Wrap). Although the efficiency of locomotion was reduced, the robot was successful in moving both forwards and backwards within the tube.

5. Discussion

We have successfully demonstrated a prototype of a robot that could locomote through tubes and around curves using peristaltic locomotion. Because the center of the robot is hollow, it can accomodate many of the instruments used within endoscopes during clinical procedures (e.g., a fiber optic light source, a camera, and tele-operated tools). It is also possible to use the device as a catheter for infusion or withdrawal of fluids.

The current prototype has several limitations.

The bladder and movable seal are both made of latex, which tend to suffer from fatigue and corrosion. Because there is a nylon mesh over the latex, and the two rub together during each cycle of contraction, the latex has a propensity to fatigue and to tear. In addition, some patients have serious allergic reactions to latex. As a consequence, it will be important to explore other polymeric materials that have similar elastic properties.

The low locomotion efficiency of the device is probably due to several factors. First, the efficiency measures were taken after the robot had been tested for many cycles, allowing significant material fatigue to reduce its efficiency. Use of superior materials could increase the robot's resistance to fatigue. Second, the robot had to pull the weight of the adapter connecting the air lines to the valve lines, which reduced its velocity. It is possible that increasing the inflation pressure and speed would allow the robot to pull larger weights with less loss of efficiency. Third, the most posterior actuator had a tendency to slip backwards when it deflated at the end of the cycle. It is possible that using a flanged bearing would provide a continued contact with the tube even after deflation and thus reduce slippage.

Finally, it will be important to demonstrate that the device can function within a biological context, e.g., within the colon or large intestine if it were to be used for sigmoidoscopy or colonoscopy. Locomotion in a hollow plastic tube is very different from locomotion in the slippery and tortuous environment of the colon. One advantage of the proposed device is that it does not use vaccuum for adhesion to the lumen wall, which has been shown to lead to accumulation of debris within the device that could affect its performance [12]. Because the material of which the device is made is very flexible, and can conform to the tortuous surfaces of the colon, and because the device has a relatively small cross-sectional diameter when it is not inflated, it is likely that it could insinuate itself into the collapsed colon and open the lumen. However, it will be important to test whether the forces generated during this process cause trauma to the internal intestinal wall or cause collapse of blood vessels that could lead to ischemia. The biomechanical properties of the intestine and a model of its response to a robotic endoscope have been recently described [14], which will aid in evaluating the efficacy of this new device.

There are several modifications that could further improve the utility of the device. First, by placing small shape memory alloy wires along the central spring, it may be possible to induce differential bending of the actuators, which will enhance its ability to maneuver through sharply angled bends. Second, it may be possible to add small sensors, e.g., MEMS-based pressure sensors, which would allow the robot to sense pressure changes due to constriction or expansion of the lumen through which it is locomoting. These sensory inputs could be fed to a neural network that could generate local reflexes, e.g., a shift from forward to backward locomotion in order to pull the robot out of a narrowing lumen. Other miniaturized sensors could allow the device to locomote towards or away from particular temperatures, sounds, light levels, or chemical compounds. Third, the device could be further miniaturized, which would allow it to serve as a catheter for blood vessels.

Several possible applications could become possible if the device were further improved. It could be used as a collar that was placed around existing endoscopes, allowing the physician to supplement his or her own attempts to position the endoscope with those of the robot. If the central lumen were more flexible, the device could also be utilized for the peristaltic transport of gases, fluids, pastes and other soft materials through its central lumen. It could also be used for the maintenance of complex plumbing in a variety of industrial contexts.

The peristaltic endoscope that we have described in this paper is another illustration of the value of biological inspiration for the development of novel robot designs. Previous work has demonstrated the value of biological inspiration for the design of legged robots and their control [23-26], and for the design of a soft-bodied hydrostatic robot [27]. Such robots are not only of interest because of their engineering applications, but because they challenge the biologist to better understand the biomechanics and neural control of the original biological organism [28, 29].

Acknowledgments

We thank Gabe Nelson for writing the control code for the sequential activation of the actuators. We thank the Ohio Board of Regents for support of this research through a Presidential Research Initiative Grant (OBR 425) to HJC, and the NSF for its support through grant IBN99-74394 to HJC. We also thank Dr. Aaron Fleischman for suggestions of potential MEMS-based sensors for this device, and Dr. Randall Beer for suggestions for control.

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