A Soft Pneumatic Maggot Robot

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Abstract. *Drosophila melanogaster* has been studied to gain insight into relationships between neural circuits and learning behaviour. To test models of their neural circuits, a robot that mimics *D. melanogaster* larvae has been designed. The robot is made from silicone by casting in 3D printed moulds with a pattern simplified from the larval muscle system. The pattern forms air chambers that function as pneumatic muscles to actuate the robot. A pneumatic control system has been designed to enable control of the multiple degrees of freedom. With the flexible body and multiple degrees of freedom, the robot has the potential to resemble motions of *D. melanogaster* larvae, although it remains difficult to obtain accurate control of deformation.

1 Introduction

We have designed a robot to mimic *Drosophila melanogaster* larvae (maggots), as a platform to test and verify their learning and chemotaxis models. *Drosophila* as a model system has a useful balance between relatively small number of neurons yet interestingly complex behaviours [10]. Many genetic techniques, such as GAL4/UAS systems developed by Brand and Perrimon [2], facilitate research on the connectivity and dynamics of the circuits. As a result, a number of necessary components of neural circuits for sensorimotor control and learning are being found and modelled. Currently, the models are tested by comparing between wildtype and genetic mutation lines, or using simulations of neural circuits and comparing output with biological experimental recordings. To test models in a wider environment, more similar to a larva, a physical agent that copies properties of the larval body is important.

Larvae have high degrees of freedom (DOFs) and flexible bodies. As a result, they are able to do delicate and spatially continuous motion. Simplified in mechanics, a larval body consists of body wall attached to the muscles and body fluids inside the body wall. The 2 parts works together as a hydrostatic skeleton [5]. The skin has regular repeating symmetrical folds, which are essential for its deformation and friction, forming its segments. The muscles of Drosophila larvae are in 3 orientations: dorso-ventral, anterioro-posterior and

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oblique. Antero-posterior muscles are located nearer the interior than dorso-ventral muscles. The body wall muscles are segmentally repeated, and in each abdominal half segment there are approximately 30 of them ([1]) (Fig. 1).

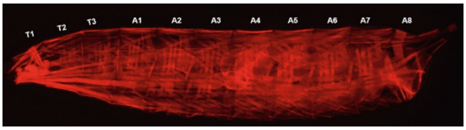


Fig. 1. A Drosophila larva expressing mCherry (a type of photoactivatable fluorescent proteins [14]) in its muscles. From Balapagos (2012).

Based on the property of their bodies, Drosophila larvae are able to do several motions, such as peristaltic crawling, body bending and rolling. Forward peristaltic motion is best described. In the centre of the body, viscera suspended in hemolymph is essential for limiting body wall deformation and produces piston motion. During the 'piston phase' of peristalsis, muscles on the tail contract and push the viscera forward. The second 'wave phase' involves a wave of muscle contraction travelling through the bodywall segments from tail to head [4]. To mimic various and motions of a Drosophila larval, it is important to utilize this anatomical structure and avoid oversimplifying the high DOFs.

Some soft robots have been developed as bionic robots. The main materials are silicone, rubber, or other flexible and stretchable materials. They are usually actuated by Shape-Memory Alloy (SMA) or pneumatically, such as Biomimetic Miniature Robotic Crawler [7], GoQBot [6], Multigait soft robot [13], and a fluidic soft robot [11]. These robots only have several degrees-of-freedom (DOFs) and usually only have one type of motion, which is not sufficient to mimic larval motion. Although SMA is widely applied on soft robots, it has a significant shortcoming. As SMAs deform according to temperature, their response is limited by control of temperature. Because soft robots are usually not sufficient in heat dissipation, heat accumulates inside the robots, and response times of SMAs get too long so that continuous actuation is infeasible. The shortcoming does not exist on pneumatic actuation. Hence, pneumatic actuators are a feasible option as they have a faster response and longer effective working time. However, the main action most of soft pneumatic actuators is off-axis bending, and the axial elongation and contraction are only side effects. For examples: Micro Pneumatic Curling Actuator- Nematode Actuator [9], Pneu-net [13]), and Robot Air Muscles made from Oogoo [8]. As axial contraction is necessary for some motion (such as peristalsis), we designed a new type of pneumatic actuators.

2 Methods

The robot is made from soft silicone rubber, instead of rigid material, because: (1) motions of Drosophila larva are based on continous body deformation; (2)

soft materials have more similar properies to biological tissue than rigid material, such as nolinear elasticity and hysteresis, which are suitable to simulate dynamic characteristics of the muscle; and (3) defomation of Drosophila larval body wall is one method to control friction between body and contacted surface.

Figure 2 shows a sketch of a possible structure of a maggot robot. The robot has repeating modular body wall segments, with a water bag or air bag inside. Here we described the construction and control of 4 body segments. At present, the control system and pneumatic system are placed off board because of limited space and load.

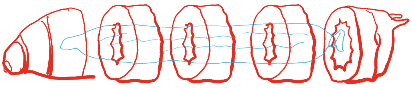


Fig. 2. Sketch of the soft maggot robot. A central bag of fluid is surrounded by muscle segments.

2.1 Design of the Actuator and Body Wall of the Soft Robot

Pneu-nets (Fig. 3(a) and (b)) are usually made from 2 different soft materials: (1) flexible and stretchable material, such as Ecoflex, to form chambers to inflate and expand; (2) flexible but less or not stretchable material, such as Polydimethylsiloxane (PDMS). Thus, when pneu-nets are inflated, the actuator bends to the side made from less stretchable material. Pneu-nets are not suitable for tubular body wall because the stretchable layer limits axial bending, hence we have modifeid the design to produce a new actuator type, which we called Extensible Pneu-nets.

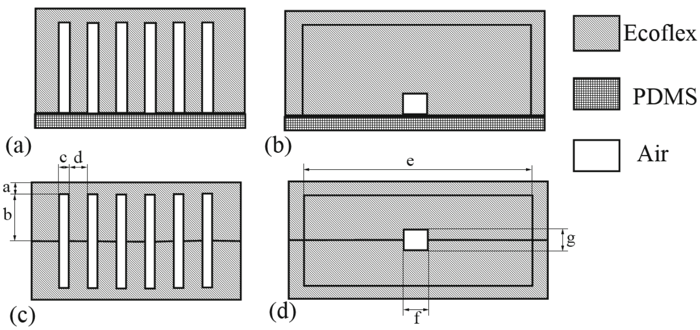


Fig. 3. Structure of Pneu-nets and Extensible Pneu-nets (a) and (b) are longitudinal and transverse sections of Pneu-nets, respectively; (c) and (d) are longitudinal and transverse sections of Extensible Pneu-nets, respectively.

Extensible Pneu-nets (Fig. 3(c) and (d)) use only 1 stretchable material. Small air chambers are connected by air tunnels to form a muscle. Different muscles are isolated. When an air chamber is inflated, it expands in all directions, and the direction with maximum expansion is the direction with the maximum cross sectional area. To limit deformation in the unwanted direction, thickness of the inner walls between chambers and thickness of the outer walls are carefully selected and tested. As stretchable material allows not only bending but also expansion along the surface, tubular body wall based on Extensible Pneu-nets are possible to axially bend.

To make the air chambers and tunnels inside, the actuator is divided into 2 layers which are cast separately. The moulds can be manufactured in conventional machining process or by 3D printing. Then the 2 layers are glued together with the same material. Finally, tubes for injecting pressed compressed air are inserted and glued. By including more air chambers and tunnels on a model, a body wall with multiple pneumatic actuators can be cast.

The first attempt at a muscle pattern was designed according to real muscle pattern on dissected and flattened body wall of Drosophila larva (Fig. 4). Dorsal oblique (DO) muscles, lateral transverse (LT) muscles, oblique lateral (LO) muscles, ventral longitudinal (VL) muscles and ventral acute (VA) muscles are simplified and mapped on the muscle pattern of the body wall. However, the adjacent muscles limited each others motions, especially when they have different orientations. The cause of limitation is that inner walls between air chambers limit transverse deformation, which is the direction that the adjacent muscles are designed to deform. Thus adjacent muscles should either be parallel, or should not be contiguous.

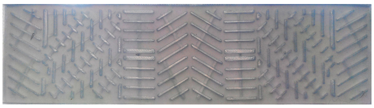


Fig. 4. Body wall of a body segment with Extensible Pneu-nets designed according to real muscle pattern on dissected and flattened body wall of Drosophila larva.

The design of the prototype evaluated in this paper is a body wall with 4 body segments (Fig. 5, left). Each body segment has 3 transverse muscles and 3 longitudinal muscles. These 2 types of muscles are connected perpendicularly and only connected on corners, leaving gaps between them to avoid limitation of deformation between each other (Fig. 5, right). Body segments are connected in series by longitudinal muscles. Figure 6 shows the mould for the body wall. After a flat body wall was made, it was folded end to end and clamped by 2 specially cut boards. Through the window of the board, the end was carefully aligned and glued together. By this process, the flat body wall is formed into a hollow cylinder shape (Fig. 7).

In this 4 body segment version, because the limited resolution of the 3D printer we use (Wanhao Duplicator with 0.4 mm nozzle) and resistance of air flow in tube, the dimensions of air chamber, as shown in Fig. 3(c) and (d), are: a = 1.2 mm, b = 3.0 mm, c = 0.8 mm, d = 1.2 mm, e = 18 mm (longitudinal muscles) or 28 mm (transverse muscles), f = 2.0 mm, g = 3.0 mm. In a curved single body segment, the longitudinal length is 40 mm, the diameter is of the robot is about 50 mm. The total length of the 4 body segment body wall is about 175 mm.

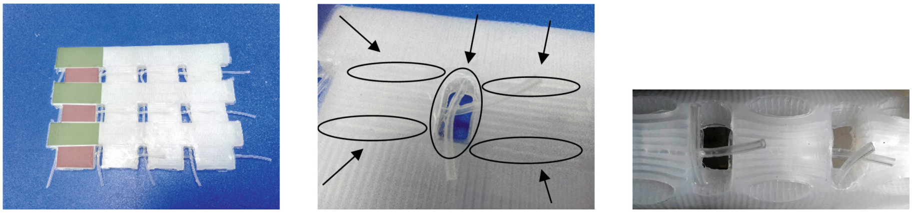


Fig. 5. (left) Prototype design of a body wall with perpendicular arrangement of muscles. Transverse muscles and longitudinal muscles of the first body segment are highlighted in red and green, respectively. (centre) A closer view of the flatten body wall shows gaps and spaces between the muscles to allow expansion. (right) The gaps and spaces when the body wall curved. (Color figure online)

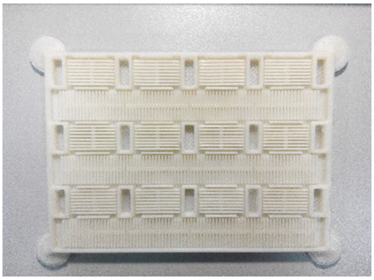


Fig. 6. The 3D printed mould for body wall casting.

2.2 Pneumatic Actuation and Control System

The pneumatic actuation and control system controls the robot by controlling air pressures of air chambers. Air pressure sensors measures pressure in every muscle, pumps and valves control the air flow.

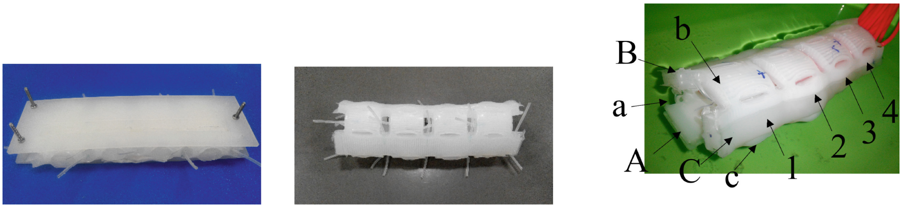


Fig. 7. (left) The body wall is clamped and glued. (centre) Formed into a hollow cylinder. (right) Names of muscles: body segments are numbered, longitudinal muscles named in capital letters, transverse muscles named in lower case letters.

Pneumatic Control System. A pneumatic control system has been designed for the robot. The system is located off board and connects to the robot with rubber tubes. As the robot has more DOFs than previous pneumatic soft robots mentioned above, the size of the pneumatic control system is designed to be compact.

The main component of the system is a valve island with 24 pairs of miniature 2 way solenoid valves (Fig. 8). The size of solenoid valves is 10 mm × 11 mm × 23 mm. Overall, the size of the valve island is 120 mm × 91 mm × 60 mm. The valves are installed the 3D main structure by interference fit. The main structure of the valve island consists of layers of 3D printed parts. The upper layer made form Acrylonitrile Butadiene Styrene (ABS), which offers Mechanical strength to fix valves, and lower layer made from Thermoplastic Elastomer (TPE), which has build in air channels with air-tightness. Every channel connects 4 ways, which are 2 valves, a pressure sensor, and an air chamber on the robot. The other 2 ways of each pair of valves are connected to compressed air and open to air, respectively. As the solenoid valves speed up to 100 Hz, the air flow can be finely controlled.

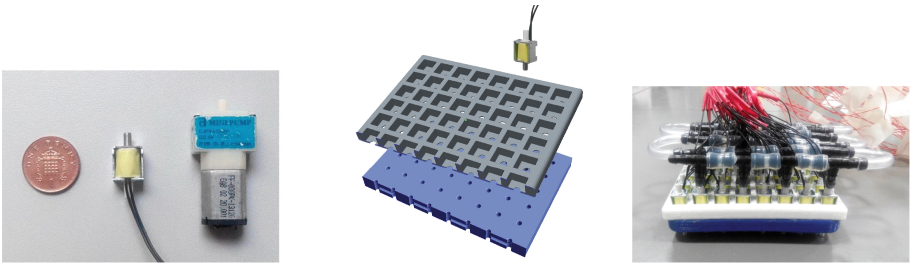


Fig. 8. (left) A valve and pump in the system. (centre) Structure of the 3D printed valve island. (right) Pneumatic valve island with 24 pairs of valves

Embedded Control System. An Embedded Control system has been designed for control and actuation. The control system is a hierarchical control system consisting of 1 main controller and 3 slave controllers. Their micro controllers are

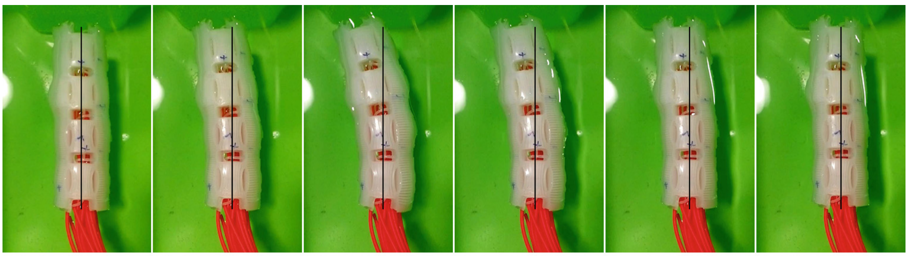
STM32F411RE by STMicroelectronics. They are based on Cortex-M4 by ARM with digital signal processor (DSP) and floating-point unit (FPU). The main controller receives commands from a computer, and distributes them among the slave controllers by Universal Synchronous/Asynchronous Receiver/Transmitters (USART). On each of the slave controllers, 16 hardware Pulse-width modulation (PWM) channels and 8 Analog-to-digital converters (ADC) are configured to control 8 muscles. The PWMs control Darlington transistor arrays (ULx2003 by Texas Instruments). On each slave control board, 3 of them are adopted to drive valves. MPS20N0040D-D, which is an air pressure sensor to measure pressure in air chambers, is adopted to measure the pressures.

Algorithm. At present stage, the robot is controlled by feedforward preprogrammed motion. According to a approximate linearization between deformation and pressure at the initial state of equilibrium, the pressure is utilized as feedback of motion of muscle.

3 Experiments

The robot was tested for individual control of every muscle and coordination between them. Three motions are programmed and tested on the robot (A video of the experiments: https://youtu.be/aFE9dANHowk). The muscles are named based on their location. As show in (Fig. 7), body segments are numbered, longitudinal muscles named in capital letters, transverse muscles named in lower case letters.

Turn. In this motion, muscle a and B on every body segment was actuated at the same time, then pressure released. To minimize friction and show relevance between pressure and deformation, the robot is tested while floating on water. Figure 9 shows the motion of the robot. The pressure of the muscles is shown in Fig. 10.



(a) 1 s (b) 4 s (c) 7 s (d) 10 s (e) 13 s (f) 15 s

Fig. 9. Turning left. The black lines show the initial central axis.

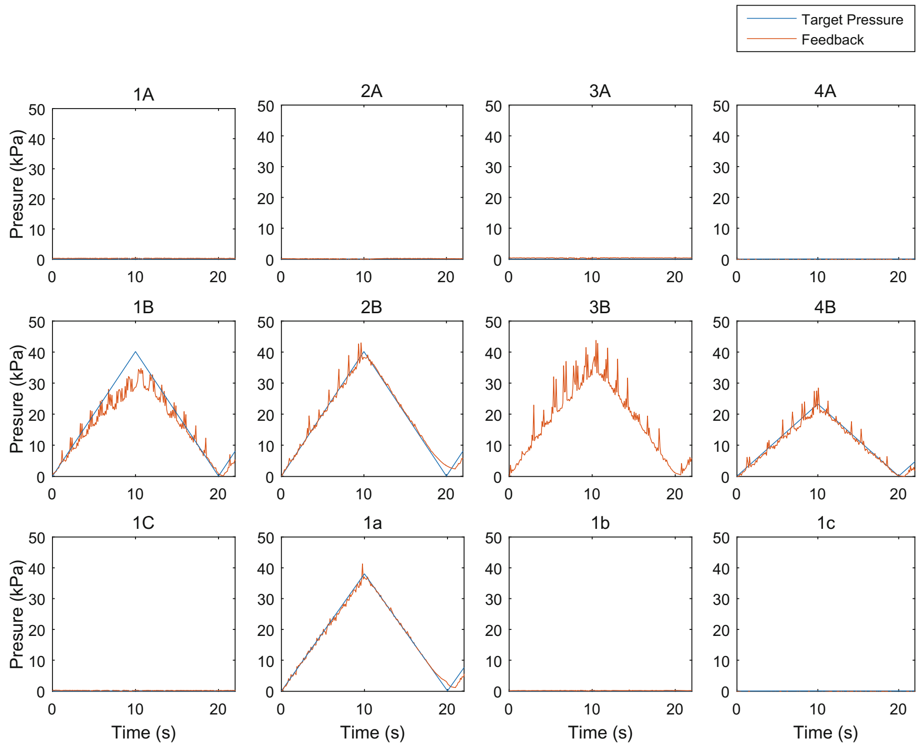


Fig. 10. Pressure of muscles in the first body segment, muscles A and muscles B during turning. (Color figure online)

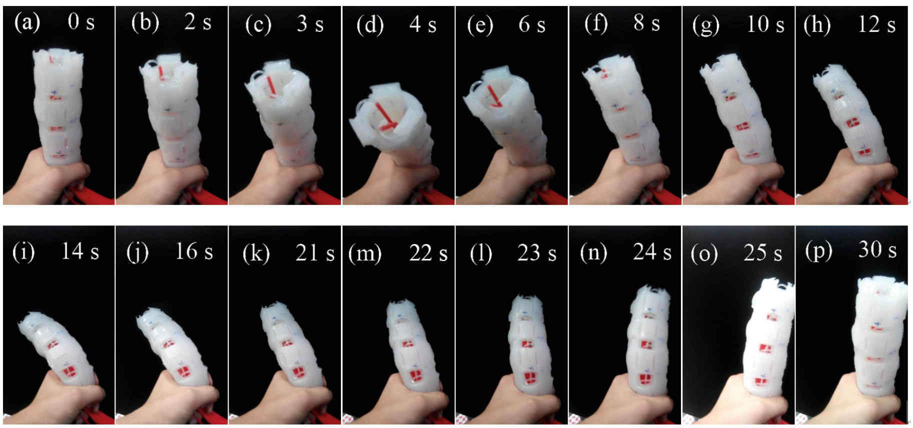


Fig. 11. Roll.

Roll. In this motion, muscle a and B, b and C, c and A, are inflated alternately. As the bundle of the tubes flowing the robot impact the rolling on a surface in water, the robot is hold on its tail vertically during test. Figure 11 shows the motion of the robot. The pressure of muscles show in Fig. 12.

Peristalsis. In this simplified peristalsis, all the muscles on a body segment inflate at same time and muscles of different segments inflate alternately.

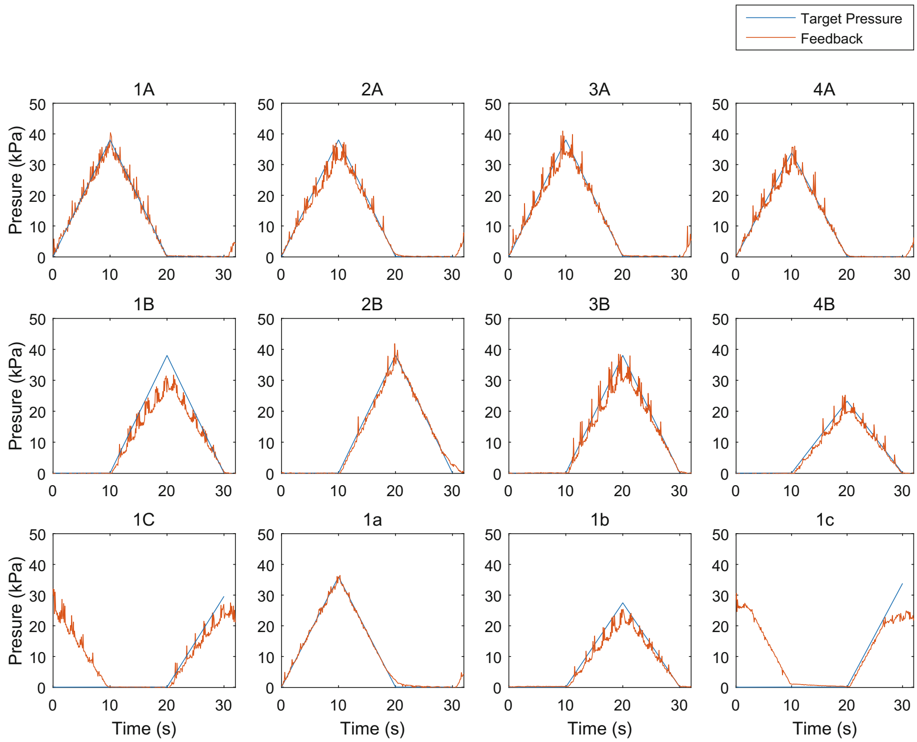
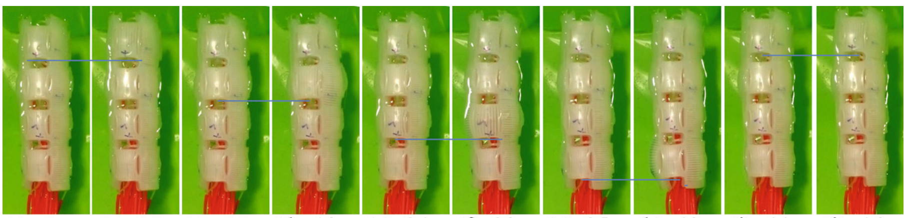


Fig. 12. Pressure of muscles in the first body segment, muscles A and muscles B during rolling. (Color figure online)



(a) 4 s (b) 10 s (c) 15 s (d) 19 s (e) 24 s (f) 29 s (g) 35 s (h) 40 s (i) 44 s (j) 46 s

Fig. 13. Peristalsis. The parts on the blue lines were expanding. (Color figure online)

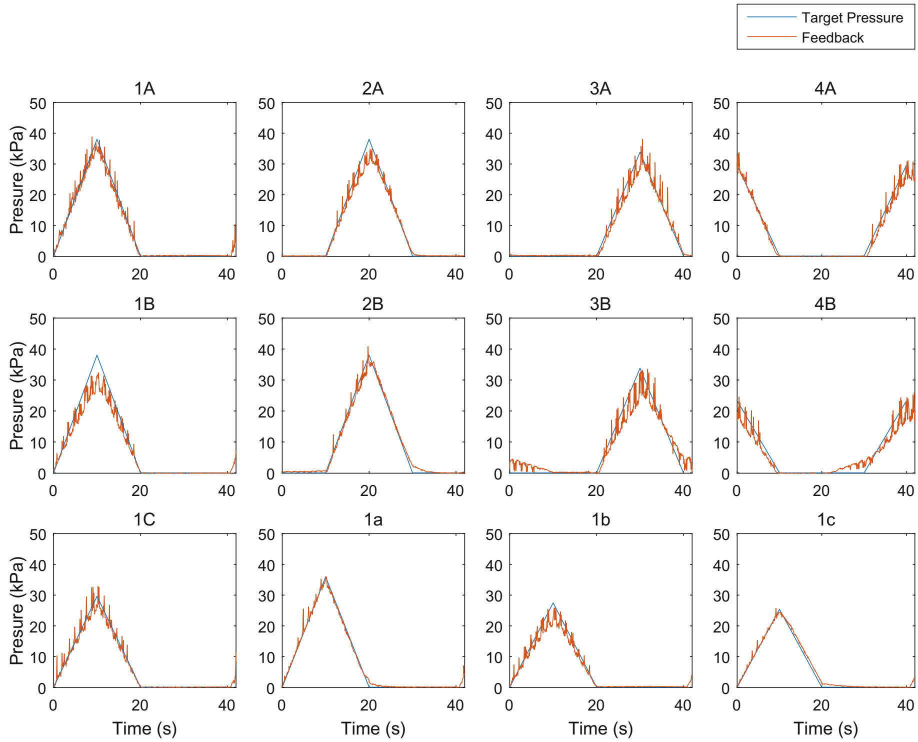


Fig. 14. Pressure of muscles in the first body segment, muscles A and muscles B during peristalsis. (Color figure online)

The motion is tested on water. Figure 13 shows the motion of the robot. The pressure of muscles show in Fig. 14.

4 Discussion

In the tests above, the robot produced three different motions from muscles actuated individually in different orders. The system was able to control the pressures according to the control signal, although the pressures have some noise. However, the three motions are not accurate. Deformation for the same pressure is different between the muscles. That is because muscles are slightly different and the relationship between deformation and pressure is not ideally linear. When an air chamber is inflated to a given range, the pressure does not change much even with obvious deformation. Hence, applying the same pressure to different muscles can result in different deformations. Thus, deformation sensors will be important to precise control of the robot.

Hence our immediate aim for future work is to develop and install sensors on the robot for deformation feedback. As the sampling density of the deformation sensors is limited, different deformations may map to the same output, hence a model or method to learn the relationship between sensor outputs and posture is necessary. We should then be able to explore more thoroughly the movement capabilities of the current design. Some additional redesign of the pneumatic muscle and body wall may be necessary, for example, surface processes to mimic denticles on Drosophila larval skin which generate asymmetric friction so that peristalsis produces forward locomotion [12].

5 Conclusion

Our longer term aim for this robot is to use it as a platform to test neural circuit models of *Drosophila* larvae. Initially this could focus on the motor circuits that generate and control peristalsis and bending. In particular these circuits could form the basis of an adaptative method for learning the control signals needed to adjust to the irregularities and non-linearities in the actuators and their interactions, in the same way that maggots are able to adapt to rapid change and growth in their body while maintaining efficient locomotion. Ultimately we would like to add sensors for environmental signals and investigate the sensorimotor control and associative learning involved in, e.g., odour search [3].

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