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Ratchet-integrated pneumatic actuator (RIPA): a large-stroke soft linear actuator inspired by sarcomere muscle contraction

Hyun Sung Cho, Tae Hwan Kim, Tae Ilwa Hong and Yong-Lae Park
Department of Mechanical Engineering, Institute of Advanced Machines and Design (IAMID), Institute of Engineering Research, Seoul National University, Seoul 08826, Republic of Korea
E-mail: ylpark@snu.ac.kr

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Abstract

Pneumatic artificial muscles (PAMs) have a wide range of robotics applications, especially in soft robots, for their ability to generate linear force and displacement with the soft, lightweight, compact, and safe characteristics as well as high power densities. However, the compressibility of the air causes a spring-like behavior of PAMs, resulting in several common issues of limited stroke, load-dependent stroke lengths, difficulty in maintaining their length against disturbance, and necessity of accurate pressure control system. To address these issues, this study borrows inspiration from a biological soft linear actuator, a muscle, and proposes a ratchet-integrated pneumatic actuator (RIPA). Utilizing two pawls integrated at both ends of a McKibben muscle and a flexible rack inserted in the middle of the muscle, the RIPA achieves a large stroke length by accumulating displacements from multiple small strokes of the McKibben muscle by repeating the cycle of pressurization and depressurization. This cycle mimics the cross-bridge model of a sarcomere, a basic unit of a skeletal muscle, in which a muscle accumulates nanoscale strokes of myosin head motors to generate large strokes. The synergy between a PAM and the inspiration from a sarcomere enabled a large-stroke soft linear actuator that can generate independent strokes from loads. The proposed actuator is not only capable of maintaining its length against unexpected mechanical disturbances but also controllable with a relatively simple system. In this paper, we describe the design of the RIPA and provide analytical models to predict the stroke length and the period per cycle for actuation. We also present experimental results for characterization and comparison with model predictions.

1. Introduction

The ability to generate linear force and displacement by simple mechanisms of pneumatic artificial muscles (PAMs) resulted in a wide range of robotics applications, especially in soft robotics [1–6]. The basic structure of this type of actuator is an inflatable bladder combined with geometrical constraints, such as a mesh [1, 2, 7, 8], embedded fibers [9–11], or simply a non-stretchable bladder material [12, 13]. These soft, lightweight, compact, and compliant actuators not only show high force-to-weight ratios [1–3] but also are relatively safe due to the use of compressed air [14, 15]. Researchers and industry are raising their interests in PAMs for these qualities.

However, PAMs show common limitations in general. The compressibility of the air causes a spring-like behavior of PAMs with damping and nonlinearity [1, 8, 10, 11], resulting in the following drawbacks. First, PAMs have limited stroke lengths as their contraction ratios are limited, like a stretched spring. Typical PAMs show contraction ratios under 35% [1, 10, 16–18]. As far as the contraction ratio is limited, the initial length should be increased to achieve large displacement, which may not be an option for certain applications. Although there have been several attempts to increase the contraction ratios directly, they increased it limitedly (20% at most) [19–21]. A muscle with a much higher contraction ratio (90%) has been proposed using a vacuum [22]. However, the force was limited in return in this case. Second, the stroke length of a PAM is correlated to the load, which is similar to the static force-displacement relationship of a spring. Although the static force that a PAM can generate is high at its
maximum length, it rapidly decreases as the displacement (i.e. contraction) increases. Also, the dependency of the stroke length on the load leads to an unreliable operational space of a robotic system with the PAM. Third, it is difficult for a PAM to maintain its contracted length when an unexpected external force (i.e. disturbance) is applied, due to the compliance of the PAM. The force-displacement relationship of a spring-like PAM makes it difficult to reject the disturbance without making any unwanted displacement. Finally, a relatively complex system capable of delicate pressure control is required for an individual PAM, since the pressure determines the stroke length. The control system may increase the weight, bulkiness, and complexity of the host system as the degrees of freedom (DOF) of the robot increases, limiting the range of applications of PAMs in robotics.

To address these issues, this study borrows inspiration from a biological soft linear actuator, a muscle. The basic unit of a skeletal muscle is a sarcomere. A sarcomere is composed of two main components, actin and myosin, and actuates with the mechanism called the cross-bridge cycle. Actin pulls myosin bit by bit in one direction repeatedly for contraction. For relaxation, the bonding part of myosin is hidden from actin and kept unattached until an antagonistic muscle contracts to pull actin and myosin in the opposite direction. There has been a study that integrated this mechanism with a shape-memory-alloy (SMA) actuator [25]. In this study, the small strokes of the SMA actuator were accumulated to rotate a geared pulley to wind a tendon around it. However, the study used a long rigid carbon pipe as a support fixture, compromising the flexibility of the actuation module.

Thus, we propose a ratchet integrated pneumatic actuator (RIPA) that mimics the behavior of a sarcomere. This new large-stroke soft linear actuator is expected to address the four common issues of conventional PAMs. First, the stroke length of the RIPA is only determined by the length of the flexible rack, which has no limit technically. Second, the stroke length of the RIPA is independent of the load. The force generated by the RIPA does not decrease with the displacement, ensuring a reliable operational space of the host robotic system. Third, the RIPA is capable of resisting a mechanical disturbance while containing structural compliance. By manipulating the ratchet system, the RIPA can easily switch the mode between compliance and rigidity for different applications. Finally, the RIPA can be controlled simply by binary valves without accurate control of input pressure.

This study focuses on the design and modeling of the RIPA. The remainder of the paper is organized as follows. The mechanisms of a sarcomere and a McKibben muscle are briefly introduced in section 1. The design and the mechanism of the RIPA inspired by sarcomere contraction is described in section 2, followed by analytical modeling in section 3. The experimental setup is shown in section 4, and the results are presented in section 5, with a comparison with the model prediction in section 3. Finally, section 6 concludes the study with discussion.

1.1. Sarcomere

Biological muscles can be categorized into three major groups; skeletal muscles, smooth muscles, and cardiac muscles. Skeletal muscles are also called voluntary muscles since they can be controlled consciously, unlike the other two types of muscles. Connected to bones via tendons, skeletal muscles play a crucial role in enabling skeletal movements of animals.

A sarcomere is the basic unit of a skeletal muscle, which consists of an actin filament and a myosin filament, as shown in figure 1(a). A myosin filament has numerous myosin head motors that make contraction of a skeletal muscle. An actin filament is surrounded by tropomyosin that enables relaxation of the muscle.

Figure 1(b) illustrates the contraction and the relaxation mechanism of a sarcomere. The contraction mechanism of a sarcomere is also called the cross-bridge model or the sliding filament model. The bottom myosin head motor in figure 1(b)-Contraction shows the four steps of each contraction cycle. First, the myosin head binds to the binding site of the actin filament. Second, it pulls the actin towards the center of the myosin. Third, it detaches from the actin. Finally, it stretches out back to the original position to repeat the cycle. By repeating this cycle, the small strokes under 38 nm [24] of the myosin head motors are accumulated to generate a greater stroke. Although the single stroke of the myosin head motors decreases as the load increases [25], this cyclic mechanism enables muscles to achieve an equal amount of total accumulated stroke even under higher loads.

The relaxation of a sarcomere requires an antagonistic muscle. As demonstrated in figure 1(b)-Relaxation, the tropomyosin surrounding the actin filament expands to hide the binding sites of the actin filament from the myosin heads. This action allows the two filaments to slide freely. In this state, the contraction of the antagonistic muscle leads to the relaxation of the sarcomere of the original muscle.

1.2. McKibben muscle

A McKibben muscle was used as a base actuator in the design of a RIPA. A McKibben muscle is a pneumatic soft linear actuator that shortens its length by the air pressure in the bladder. The structure of a McKibben muscle is shown in figure 2. Each thread of nylon mesh is inextensible, so its length, \( b \), is constant. An elastomeric bladder is inserted inside the mesh. The expansion of the bladder by the air pressure induces the increase of the diameter, \( D \), of the shell in the radial direction. Then, the length of the McKibben muscle, \( l \), decreases from the relationship illustrated in the triangle of figure 2.

According to the static model of a McKibben muscle, derived by [1], \( F \) can be expressed as
Figure 1. Introduction to a sarcomere. (a) A structure of a skeletal muscle and a sarcomere. A sarcomere is a basic unit of a skeletal muscle. (b) Mechanisms of contraction and relaxation of a sarcomere. A sarcomere consists of two filaments, actin and myosin. For contraction, myosin head motors repeat a 4-step cycle of (i) attaching to the myosin, (ii) pulling the myosin, (iii) detaching from the myosin, and (vi) stretching back to the original position. For relaxation, (v) tropomyosin surrounding the myosin expands and hides the actin-binding sites, allowing the two filaments to slide freely.

Figure 2. A structure and a mechanism of a McKibben muscle. (a) A structure of a McKibben muscle. An elastomeric bladder is inserted inside the mesh. (b) Each thread of a nylon shell is wound n times on the bladder. (c) Each thread is inextensible. Thus, the increase of the diameter, $D$, of the shell by the air pressure inside the bladder induces the decrease of the length, $l$, of the McKibben muscle according to the Pythagorean theorem.

$$F = \frac{P' b \ell (3 \cos^2 \theta - 1)}{4 \pi n^2}$$

(1)

where $P'$ is a relative pressure inside the bladder, $\theta$ is an angle between the thread and the axis of the bladder, and $n$ is the number of turn of the thread around the bladder.

From (1), it is obvious that $F$ becomes zero, and a McKibben muscle stops contracting when $\theta$ reaches $\theta_0$, which satisfies $\cos \theta_0 = \frac{1}{\sqrt{3}}$.

Under the assumption that the displacement of the McKibben muscle from the zero force-length $(l_0)$, $u$, satisfies $u \ll b$, (1) can be expressed as


\[ F = \frac{P'}{4\pi n^2} (3l_0 + u)^2 - b^2 \approx \frac{P'}{4\pi n^2} (6b_0 + 3l_0 - b^2) \]  

(2)

Since \( l_0 = b \cos \theta_0 = b/\sqrt{3} \), the constant term \( 3l_0 - b^2 \) becomes 0. Thus,

\[ F \approx ku \]  

(3)

where \( k = \frac{P'}{4\pi n^2} (6b_0) \) is the equivalent spring coefficient of the McKibben muscle. Note that the direction of \( u \) and \( F \) is the opposite.

This conventional model of the McKibben muscle indicates that it behaves like a stretched spring. Thus, the stroke is limited and force-dependent, similar to the behavior of the myosin head motors of a sarcomere.

2. Design and mechanism

The design of the RIPA is illustrated in figure 3. Two paws were installed at both ends of a McKibben muscle. There is a through-hole in the middle of the McKibben muscle in the vertical direction for a flexible rack (i.e. a cable tie) to be inserted. Since the rack always passes the paws with contacts, it can only move upward. Each paw was joined with a rubber band that pushes the paw towards the rack for engagement. A mini-bag actuator at the top of each paw releases the engagement of the paw with the rack by pushing it away from the rack when pressurized. This simple actuator is a small airbag made of a heat-shrink tube with one end sealed. Although the material of the airbag is not stretchable, it is flexible and airtight. Thus, it can be collapsed by the rubber band when deflated but can push the paw away from the rack when inflated.

The RIPA has three input air channels. Two of them are connected to the mini-bag actuators, and the other is connected to the McKibben muscle. There is an inner layer that separates the actuation space of the muscle from the ratchet space. It prevents the air for the McKibben muscle from leaking out from the through-hole for the rack. Also, there is a robust yet flexible tube inside the upper part of the inner layer. It prevents jamming of the rack by the inner layer, which impedes the rack’s motion.

The total length of the RIPA prototype without the flexible rack is 200 mm. The length and the diameter of the McKibben muscle vary from 100 to 73 mm and from 16 to 23 mm, respectively, when absolute input pressures under 600 kPa are applied. The length of the flexible rack is 500 mm, and the total weight of the RIPA, including the rack, is 53 g.

2.1. Mechanism

Figure 4(a) illustrates the mechanism of the RIPA. The RIPA generates linear displacement between the two fixing points, the top end of the McKibben muscle and the bottom of the flexible rack. The left spring represents the McKibben muscle. When the McKibben muscle is pressurized, the bottom paw engages to the rack and pulls the rack up. After pulling it up, the McKibben muscle is depressurized. Then, the bottom paw slides down the rack back to the original position while the top paw is holding the rack. By repeating this cycle, the RIPA can accumulate a large displacement.

The relaxation of the RIPA is a passive process. The two mini-bag actuators are inflated to push the paws away, hiding the rack from the paws for relaxation. In this state, a small force pulling the RIPA down can slide the rack out of the McKibben muscle to the maximum length. In theory, it is possible to control the relaxation process by regulating the inflation time of the mini-bag actuators. However, the precise control of relaxation of the RIPA requires an antagonistic pair, similar to biological muscles. In a system with antagonistic pairs, the RIPA undergoing a relaxation process will stay passive and comply with the controlled contraction of the antagonistic RIPA.

As can be seen from figure 4, there is a close analogy between the mechanism of the RIPA and that of a sarcomere. The McKibben muscle, the paws, the rack, and the mini-bag actuators correspond to a myosin filament, myosin heads, an actin filament, and tropomyosin, respectively.

Figure 5 illustrates the two clutch modes of the RIPA. The rigid clutch mode depicted in figure 5(a) allows the RIPA to reject an external disturbance without making any displacement. The RIPA can be switched to this mode by deflating the top mini-bag actuator. In the soft clutch mode illustrated in figure 5(b), the RIPA can react to an external disturbance with compliance, reducing the peak impact force applied to the system by dissipating the energy from the impact to the McKibben muscle. The actuator can switch to this mode by simply inflating the top mini-bag actuator, maintaining the deflated state of the bottom mini-bag actuator. During this mode, the McKibben muscle should be kept pressurized to provide mechanical compliance (i.e. shock absorption).

The McKibben muscle and the mini-bag actuators of the RIPA can be operated by simple binary valves. Thus, the RIPA can be controlled with three-way solenoids without the necessity for delicate pressure control modules. This not only reduces the weight of the host system but also significantly simplifies the control hardware, making the RIPA advantageous for high DOP systems.

2.2. Fabrication and assembly

Figure 6 shows the components used to assemble a RIPA. Most components went through several steps before the assembly. First, the McKibben muscle layer (2) was made of a braided insulation sleeve (FR Silicone Flex Glass, Techflex). It was cut and flipped inside out. Second, the inner layer (3) was made from heat sealable fabric (nylon fabric coated by thermoplastic polyurethane). It was folded and heat sealed to form a tube. Third, the inner tube (4) was fabricated by
inserting an air tube with an outer diameter of 8 mm into a 12 mm tube. Fourth, the plastic pieces (6, 9, 10, 11) and the pawls (8) were 3D printed with rigid plastic (VeroBlack, Stratasys). The mini-bag actuators (14, 15) were made from a 2 mm air hose and a heat shrink tube (17). Cyanoacrylate glue was applied to the end of the air hose and then inserted into the heat shrink tube. The tube was shrunk to fit the hose by a heat gun. Then, the other end of the tube was sealed with an impulse heat sealer.

A RIPA can be assembled with the components of figure 6 with four steps. First, the layers (2, 3, 4, 5) were assembled with the main pieces (6, 10). Both ends of the McKibben muscle layer (2) were rolled up, and the inner layer (3) was inserted into it. Then, the inner tube (4) was inserted into the upper part of the inner layer and fixed with a cable tie (5). Both ends of the inner layer were fit to the main pieces (6, 10). Second, the air hoses (14, 15, 16) were inserted. The mini-bag actuator for the bottom pawl (14) was integrated with the bottom main piece (10). The air hose of it was further inserted to the bottom side piece (11) and the space between the McKibben muscle layer and the inner layer. Then, that and the air hose for the McKibben muscle (16) were inserted to the top side piece (9) and the top main piece (6). The mini-bag actuator for the top pawl (15) was integrated with the top main piece. Third, the layers were firmly fixed to the main pieces. The side pieces were attached to the main pieces, and the O rings (7) were applied to hold the main pieces, the inner layer, and the side pieces together. Both ends of the McKibben muscle layer were rolled down and fixed by the hose bands (13). Fourth, the ratchet parts (8, 12, 19) were integrated. The pawls (8) were inserted into the main pieces, and the rubber bands were applied around them and the pawls. Then, the flexible rack was inserted to the through-hole, penetrating the bottom main piece, the inner layer, the inner tube, and the top main piece in order. After these four steps, the RIPA was ready to be connected to the pneumatic system by the one-touch fittings (18).

3. Modeling

The main actuation mode of the RIPA is contraction. Relaxation of the RIPA is passive and controlled by an antagonistic force. Thus, a model for contraction was mainly considered in this work to suggest a control strategy of the RIPA. As the RIPA is a cyclic actuator, the stroke per cycle, according to the force applied to the RIPA, and the period of each cycle, according to the pressurization time, are modeled.

3.1. Maximum stroke per cycle

Unlike conventional McKibben muscles, a sufficient radial spring coefficient of the bladder is important and should be included in the model. It is utilized to push the bottom pawl back down to the original
position and to make the bottom pawl glide against the rack.

The model of the maximum stroke per cycle according to the force applied to the RIPA that involves the spring coefficient of the bladder was developed from the static force equilibrium equation under several assumptions: (i) the maximum stroke per cycle is equivalent to the stroke of the static equilibrium state of the McKibben muscle, (ii) the spring effect of the bladder is dominant in radial direction compared to the axial direction, (iii) the damping effect of the bladder is negligible, (iv) the effect of the top and the bottom edges of the McKibben muscle is negligible, (v) the flexible rack only moves upward during the whole contraction, and finally (vi) the flexible rack does not buckle inside the McKibben muscle.

From figure 2(c), the radius of the RIPA, $r$, and $\cot \theta$ can be expressed as

$$ r = \frac{D}{2} = \frac{\sqrt{b^2 - \bar{b}^2}}{2 \pi n} $$

and

$$ \cot \theta = \frac{F}{2 \pi n r'}. $$

The vertical and the circumferential force applied to the bladder and the threads by the air pressure is illustrated in figure 7(a). The sum of the vertical components of the tension of each thread should be equivalent to the sum of the force applied to the RIPA, $F$, and the vertical force by the air pressure, $P' \pi r^2$ where $P'$ is the relative air pressure. The sum of the horizontal components of the tension of each thread and the tension of the bladder should be equivalent to the circumferential force by the air pressure, $P' r l$. Thus, as shown in figure 7(b), $\cot \theta$ can also be expressed as

$$ \cot \theta = \frac{(P' r l - F_{bladder})/nx}{(P' \pi r^2 + F)/x}. $$

From (5) and (6), the force the RIPA can pull at the static equilibrium can be derived as

$$ F = \frac{(P' r l - F_{bladder}) \cot \theta}{n} - P' \pi r^2 $$
Figure 5. Clutch modes of the ratchet integrated pneumatic actuator (RIPA). (a) Rigid clutch mode. The RIPA can be switched to this mode by deflating top mini-bag actuator. In this mode, two fixing points are not connected by the McKibben muscle. Thus, the RIPA can resist an external disturbance without making any displacement in this mode. (b) Soft clutch mode. The RIPA can be switched to this mode by inflating the top mini-bag actuator, deflating the bottom mini-bag actuator, and pressurizing the McKibben muscle. In this mode, two fixing points are serially connected to the pressurized McKibben muscle, which shows spring-like behavior. Thus, the RIPA can react compliantly to an external disturbance, reducing the peak impact force applied to the system.

Figure 6. Components of the RIPA. 1-Unflipped McKibben muscle layer. 2-Flipped McKibben muscle layer. 3-Inner layer. 4-Inner tube. 5-Cable tie for fixation between the inner layer and the inner tube. 6-Top main piece. 7-O ring. 8-Pawl. 9-Top side piece. 10-Bottom main piece. 11-Bottom side piece. 12-rubber band. 13-Hose band. 14-Mini-bag actuator for the bottom pawl. 15-Mini-bag actuator for the top pawl. 16-Air hose for the McKibben muscle. 17-Heat-shrink tube. 18-One-touch fitting between the air hose with outer diameter 2 mm and 4 mm.
\[ P' = P \left( \frac{r^2}{2 \pi n^2} - \pi r^2 \right) - \frac{k_{\text{bladder}} (r - r_i) l}{n^2 r} \]  
(8)

\[ P' = P \left( \frac{1}{4 \pi n^2} (2b^2 - b^2 - l^2) \right) - \frac{k_{\text{bladder}} l}{n^2} \left( 1 - \sqrt{\frac{b^2 - l^2}{b^2 - l^2}} \right) \]  
(9)

\[ (P - P_0) \frac{3l^2 - b^2}{4 \pi n^2} = \frac{k_{\text{bladder}} l}{n^2} \left( 1 - \sqrt{\frac{b^2 - l^2}{b^2 - l^2}} \right) \]  
(10)

where \( k_{\text{bladder}} \) is the radial spring coefficient of the bladder, \( P \) is the absolute pressure, \( P_0 \) is the absolute ambient pressure, \( n \) is the number of threads, \( r_i \) and \( l \) are the initial radius and the length of the McKibben muscle, respectively.

For \( 0 < l < b \), \( dP/dl \) is positive, since the derivatives of both terms including \( l \) of (10) are positive. This proves that the function between \( l \) and \( F \) is bijective for the operating range of \( l \) of the RIPA. Thus, under the first assumption, it is possible to acquire the maximum stroke per cycle, according to the loads, from (10).

3.2. Period of each cycle

The period of each cycle is the sum of the time spent for pressurization and depressurization. Since a McKibben muscle generates the maximum force when \( l \) is the maximum (i.e. \( l = l_i \)), this study suggests to depressurize the RIPA until the bottom paw reaches the initial position before repeating a new cycle. The depressurization time, so as the period of each cycle, required to meet this condition differs by pressurization time. Pressurization and depressurization of the RIPA are schematized as a charge and a discharge process of a volume-changing air tank via a narrow pipe with the length, \( L = 70 \) mm, and the diameter, \( D = 0.85 \) mm, respectively. With this scheme, the period of time according to the pressurization time can be obtained under several assumptions: (i) the pipe is sufficiently narrow that the air charge and discharge happen slow enough for the system to maintain the static force equilibrium, (ii) the pressure at the outlet of the regulator is instantly switched between the ambient and the source pressure, (iii) the entire process is isothermal as the pipe is significantly narrow, and finally (vi) the Darcy friction factor, \( f_d \) is constant for the entire process. Referring to the Moody chart, the \( f_d \) is approximated as 0.035 since the Reynolds number and the relative roughness of this system are around 10^4 and 0.002, respectively.

From (10), the absolute pressure inside the RIPA with the length of the McKibben muscle, \( l \), and force by the weight held, \( F \), can be derived as

\[ P = P_0 + \frac{4 \pi k_{\text{bladder}} l}{3l^2 - b^2} \left( 1 - \sqrt{\frac{b^2 - l^2}{b^2 - l^2}} + \frac{n^2 F}{k_{\text{bladder}} l} \right). \]  
(11)

Also, the volume of the McKibben part, \( V \), can be expressed as

\[ V = \pi r^2 l = \frac{(b^2 - l^2) l}{4 \pi n^2}. \]  
(12)

Under the assumption of an isothermal process with ambient temperature, \( T_0 \), the density of the air inside the McKibben layer, \( \rho \), can be derived from the ideal gas law, \( P = \rho RT \), where \( R \) is the specific gas constant of dry air, as

\[ \rho = \frac{P}{RT_0}. \]  
(13)

The Bernoulli equation for compressible fluid in a pipe can be written as

\[ \frac{d}{dx} \left( \frac{v^2}{2} \right) + \frac{1}{\rho} \frac{dP}{dx} = -\frac{1}{\rho} \frac{dP_{\text{loss}}}{dx} \]  
(14)

where \( v \) and \( \rho \) are the velocity and the density of the air at a certain point of the pipe, respectively. \( dP \) and \( dP_{\text{loss}} \) are the absolute pressure difference and the pressure
loss by the friction of the pipe wall across the small length around the point, respectively.

From the continuity equation, the mass flow rate is constant for every point in the pipe. Then,

\[ \dot{m} = \rho A v = \text{const} \quad (15) \]

where \( \dot{m} \) is the mass flow rate at a certain point, and \( A \) is the cross-sectional area of the pipe which can be expressed as

\[ A = \pi D^2 / 4. \quad (16) \]

From the Darcy–Weisbach equation, \( dP_{\text{loss}} \) can be expressed as

\[ \frac{dP_{\text{loss}}}{dL} = f_D \frac{\dot{m}^2}{2A} \frac{v^2}{D}. \quad (17) \]

Combining (15) and (17) into (14) results in

\[ d \left( \frac{m^2}{2(\rho A)^2} \right) + \frac{1}{\rho} dP = -\frac{f_D m^2}{2D(\rho A)^2} dL. \quad (18) \]

Multiplying both sides by \( \rho \) results in

\[ \left( \frac{m^2}{2A^2} \right) \rho^2 d \left( \frac{1}{\rho} \right) + \rho dP = -\frac{f_D m^2}{2DA^2} dL. \quad (19) \]

From (13), it can be written as

\[ \left( \frac{m^2}{2A^2} \right) \frac{1}{\rho^2} d(P^{-2}) + \frac{1}{RT_0} P dP = -\frac{f_D m^2}{2DA^2} dL. \quad (20) \]

By integration, (20) becomes

\[ \frac{m^2}{A^2} \ln \left( \frac{P_{\text{high}}}{P_{\text{low}}} \right) + \frac{1}{2RT_0} \left( P_{\text{low}}^2 - P_{\text{high}}^2 \right) + \frac{f_D m^2}{2DA^2} L = 0. \quad (21) \]

Thus, the mass flow rate from high pressure to low pressure through the pipe \( \dot{m} \) can be expressed as

\[ \dot{m}_{\text{high to low}} = A \sqrt{\left( \frac{1}{2RT_0} \left( \frac{P_{\text{low}}^2 - P_{\text{high}}^2}{\ln(P_{\text{high}}/P_{\text{low}}) + (f_D L/2D)} \right) \right)}. \quad (22) \]

This holds until the flow remains unchoked. The choked condition occurs when the downstream velocity, \( v_{\text{exit}} \), reaches the speed of sound, \( v_{\text{sound}} \). The condition can be written as

\[ v_{\text{exit}} = \frac{\dot{m}}{\rho A} \leq v_{\text{sound}}. \quad (23) \]

For the choked flow, the mass flow rate is independent of the low pressure. The flow builds as if the low pressure is the critical pressure, \( P_{\text{critical}} \) which satisfies

\[ v_{\text{exit,critical}} = v_{\text{sound}} = \frac{\dot{m}}{\rho_{\text{critical}} A} = \frac{\left( \sqrt{\frac{1}{2RT_0} \left( \frac{P_{\text{high}}^2}{P_{\text{high}}^2} - \frac{P_{\text{low}}^2}{P_{\text{low}}^2} \right)} \right) \ln(P_{\text{high}}/P_{\text{low}}) + (f_D L/2D)}{\rho_{\text{critical}}} \]. \quad (24) \]

where \( v_{\text{exit,critical}} \) and \( \rho_{\text{critical}} \) are the velocity and the density of the air at the exit in critical condition. \( P_{\text{critical}} \) can be found by iteration.

For pressurization, the length of the McKibben muscle, thus the volume is constant until the pressure reaches \( P_{\text{p,boundary}} \) according to (11), where the subscript \( p \) indicates pressurization. Thus,

\[ P_{\text{p,boundary}} = P_0 + \frac{4\pi k_{\text{bladder}} l}{3R^2 - b^2} \left( \frac{n^2 F}{k_{\text{bladder}}l} \right). \quad (25) \]

Similarly, for depressurization from the source pressure, the volume of the McKibben muscle is constant until the pressure drops to \( P_{\text{d,boundary}} \) according to (11) where the subscript \( d \) indicates depressurization. \( l_{p_{\min}} \) is the minimum length achieved during the previous pressurization, which can be obtained from (10). Thus,

\[ P_{\text{d,boundary}} = P_0 + \frac{4\pi k_{\text{bladder}} l}{3R^2 - b^2} \left( 1 - \sqrt{\frac{b^2 - l_{p_{\min}}^2}{b^2 - l^2}} \right). \quad (26) \]

By applying the finite difference method to (13), the mass flow rate going out from the RIPA can be expressed as

\[ \dot{m}_{\text{n}} \approx \frac{P_{\text{n}} V_{\text{n}} - P_{\text{n-1}} V_{\text{n-1}}}{t_{\text{n}} - t_{\text{n-1}}} = \frac{P_{\text{n}} V_{\text{n}} - P_{\text{n-1}} V_{\text{n-1}}}{RT_0 (t_{\text{n}} - t_{\text{n-1})}}. \quad (27) \]

Note that each state \( n \) can be defined by the fine steps of \( P \) from \( P_0 \) to \( P_{\text{p,boundary}} \) with the constant \( V \), and then the fine steps of \( l \) from \( l_{p_{\min}} \) to 10 mm.

As the directions of the airflow are different between pressurization and depressurization, relation between (22) and (27) can be expressed as

\[ \dot{m}_n = \dot{m}_{\text{high to low}} \quad (28) \]

and

\[ \dot{m}_d = -\dot{m}_{\text{high to low}} \quad (29) \]

where, \( \dot{m}_n \) and \( \dot{m}_d \) are the mass flow rates going into and out from the RIPA, during pressurization and depressurization, respectively.

Thus, the time at the step \( n \) can be obtained from the equation

\[ t_{\text{p,n}} = t_{\text{p,n-1}} + \frac{P_{\text{p,n}} V_{\text{n}} - P_{\text{p,n-1}} V_{\text{n-1}}}{ART_0} \left( \frac{\ln(P_{\text{n}}/P_{\text{p,n}})}{(RT_0/2)(P_{\text{p,n}}^2 - P_{\text{n}}^2)} \right) \quad (30) \]

and

\[ t_{\text{d,n}} = t_{\text{d,n-1}} - \frac{P_{\text{d,n}} V_{\text{n}} - P_{\text{d,n-1}} V_{\text{n-1}}}{ART_0} \left( \frac{\ln(P_{\text{n}}/P_{\text{d,n}})}{(RT_0/2)(P_{\text{d,n}}^2 - P_{\text{n}}^2)} \right) \quad (31) \]

where variables with denotation \( p \) and \( d \) show that they are describing pressurization and depressurization, respectively.

From (30) and (31), the pressure-time plot of the model can be obtained. The period of each cycle required for the pressure to reach the ambient again, according to the pressurization time, can be acquired by the following steps. First, the final pressure and
the volume of pressurization at the given pressurization time can be obtained from the plot of pressurization. Second, the step \( n_p \) of depressurization, corresponding to the final pressure and volume of the pressurization, can be obtained from the plot of depressurization. Third, the required depressurization time can be obtained by subtracting the time, corresponding to the step \( n_p \), from the time, when the pressure is sufficiently close to the ambient, from the same plot. In this paper, the sufficiently close pressure is chosen to be 105 kPa, which is around 1% of the difference between the source pressure and the ambient pressure above the ambient pressure. Finally, the period per cycle can be acquired by the sum of the pressurization time and depressurization time. By the first assumption, this value is the same as the period required for the bottom pawl to reach sufficiently close to the initial position.
4. Experiment

The experimental setup is illustrated in figures 8 and 9. The control system consists of three pressure regulators (SMC ITV2050-033BL for a McKibben muscle and SMC ITV2050-312BL2 for mini-bag actuators), a power supply, an air compressor (AIRMAKER NCP 011-T3), and a microcontroller (Arduino Uno Rev3). The regulators for the McKibben muscle and the mini-bag actuators are used as on-off binary valves from the atmospheric pressure to 600 kPa and 300 kPa, respectively, if not otherwise mentioned.

Three air tubes from each regulator are connected to the RIPA. The top of the McKibben muscle of the RIPA was fixed to the Aluminium stand, and a weight was hung at the bottom of the rack. Visual markers were attached at the bottoms of the McKibben muscle and the rack. The RIPA was operated by repeating the cycle of pressurization and depressurization of the McKibben muscle. The default periods of the set-time of the pressurization and the depressurization were 600 ms and 1000 ms, respectively.

The behavior of the RIPA was analyzed by a video camera (Galaxy Note 4 SM-N916K), a pressure
sensor (SMC ITV2050-312BL2), a tensile tester (ESM-303), and a ruler. The regulator for the bottom mini-bag actuator was also used as a pressure sensor for certain experiments. The video camera recorded the experiments at 59.6 frames per second, and a pixel corresponded to 460.8 μm. The pressure sensor had a resolution of 1.28 kPa and collected data in every 10 to 21 ms. A tensile tester was operated in 1 mm s⁻¹. The data collected from this sensing system were sent to the computer to be analyzed by MATLAB.

A total of four sets of experiments were conducted. The first group was to validate the contraction and the relaxation mechanisms of the RIPA. The accumulation of the stroke was verified by the video camera with a weight of 5 kg hung to the RIPA. The relaxation of the RIPA was also tested with a weight of 200 g. For all the other experiments except for the relaxation test, the regulator for the bottom mini-bag actuator was used as a pressure sensor.

The purpose of the second experiment was to verify the model between the stroke per cycle and the weight or the force applied to the RIPA. To determine the equivalent spring constant of the bladder and the length of each thread, the length of the McKibben muscle of the RIPA was measured with the ruler under various air pressure levels, ranging from the ambient pressure to 600 kPa, without hanging a weight. The RIPA was perfectly depressurized before each measurement. Next, each set of 20 cycles of pressurization and depressurization of the RIPA with weights of 2.5, 5, 7.5, 10, and 11 kg was recorded with the video camera.

The third experiment was conducted to validate the model of the period of the cycle. The pressure during the set of 20 cycles of the RIPA was measured with sufficient time of pressurization and depressurization of 3000 ms each, and with a 5 kg weight. Next, the same operation was examined by the pressure sensor and the video camera with the pressurization time from 100 to 600 ms with 100 ms step, and the depressurization time of 1000 ms.

The last group compared the clutch modes of the RIPA. The RIPA was fixed to the tensile tester with 50 mm of the flexible rack extruded down. Then the tensile force was measured while elongating it with a speed of 1 mm s⁻¹ until the force reached 150 N. The rigid and the soft clutch modes with absolute pressures of 200 kPa and 500 kPa applied to the McKibben muscle were compared.

5. Results and discussion

5.1. Contraction and relaxation characteristics

Figures 10(a) and (c) shows the successful accumulation of strokes of the RIPA during contraction under 5 kg. The snapshots are taken at 5 cycles or 8 s interval. It reached over 250 mm after 20 cycles in sharp contrast to the PAM displacement, which is the displacement of the bottom of the McKibben muscle, fluctuating below 30 mm. The stable repetitions of the identical cycles prove the first two advantages of the RIPA. First, the stroke length can be elongated freely just by preparing a sufficiently long rack. Second, the force the RIPA can generate is identical for every cycle, and thus, the identical strokes from the cycles can always be accumulated until the limit of the length of the flexible rack, regardless of the stroke length of each cycle. Hence, the total accumulated stroke length is independent of the load, promising a reliable operational space of the host robot.

Figure 10(b) illustrates two types of loss of the RIPA. The first is from the buckling of the flexible rack when the McKibben muscle pulls the bottom paw up. Due to the slight bending of the rack, the displacement of the bottom paw is not fully transmitted to the top paw. The second type of loss is caused by friction. When the McKibben muscle relaxes, the friction between the bottom paw and the rack impedes
the complete return of the pawl to its original position. The RIPA pulls the rack this much shorter in the next pressurization, so the loss by friction is generated.

Figure 10(c) shows successful relaxation of the RIPA under 200 g. The weight fell freely shortly after both the mini-bag actuators were inflated. However, the relaxation failed under 2.5 kg, since the pushing force of the mini-bag actuators were not high enough to overcome the engaging friction between the pawl and the rack. This can be easily addressed by increasing the force of the mini-bag actuator in design.

5.2. Maximum stroke per cycle
Figure 10(d) compares the trend line and the experimental data of the lengths of the McKibben muscle under various pressure levels. It validates the model and the obtained set of values of an equivalent circumferential spring coefficient of bladder, $k_{\text{bladder}} = 1990 \text{N m}^{-1}$, and the equivalent thread length, $b = 121 \text{ mm}$. These values minimize the root mean square error (RSME) of the trend line from the experimental data under 10 N m$^{-1}$ and 1 mm resolution for $k_{\text{bladder}}$ and $b$, respectively.
Figure 11(a) shows the displacement of the RIPA under several weights. Under the controlled period per cycle, the mean contraction speed varies by weight, since the mean stroke of the RIPA per cycle varies by weight, as shown in figure 11(b). However, the maximum total accumulated stroke length is still independent of the load. Although it takes more cycles and time to reach the same displacement under a larger load, the maximum displacement is only limited by the length of the flexible rack. The distortion of the 11 kg curve after 25 s shows the failure of the ratchet. Thus, the force capacity and the maximum stress calculated with the maximum cross-sectional area are 98 N and 0.21 MPa, respectively. However, the maximum stress can be further increased by using stronger materials for the rack and the pawls. The 2.5 kg plot shows the behavior when the end of the rack reaches the bottom pawl. The error between the mean stroke of the RIPA per cycle and the model, in figure 11(b), is due to the losses by buckling and friction. The mean stroke of PAM per cycle is larger than the model due to the overshoot of the mass-spring system.

5.3. Cycle period
Figures 12(a) and (b) compare the experimental data with model predictions of pressure profiles of the pressurization and the depressurization, respectively. The pressurization showed larger errors compared to the depressurization. This is because the pressure of the regulator cannot increase to the source pressure instantly due to an additional air path between the compressor and the regulator. In contrast, the pressure can drop quickly to the ambient pressure when the depressurization starts by opening the exhaust valve of the regulator.

Another primary error source for both processes is the assumption of a constant Darcy friction factor. A Darcy friction factor is dependent on the Reynolds number of the fluid, thus so as on the velocity of the flow. According to the Moody chart, the Darcy friction factor generally increases as the flow velocity decreases. This explains the discrepancy between the gradient of the experiment and model plots of figure 12(a) at first when the velocity is low as the air just started to flow.

Figure 12(c) shows the similarity between the experiment and the model of the pressure drop profile after varied pressurization time. As figure 12(d) demonstrates, the actual periods of cycles are always slightly larger than the model. The period is defined as the time required from the start of the pressurization to the point where pressure drops below 105 kPa, which is approximately 1% of difference between the source pressure and the ambient pressure above the ambient pressure.

The error is mainly due to the delay of the regulator. When exhausting the air from the muscle, we observed a mechanical delay in closing the valve from the air compressor. The portion of the pressurized air flowed into the McKibben muscle and induced the slight pressure rise even after the end of the pressurization period. The lower the pressure of the McKibben muscle is, the more portion of the pressurized air can flow in. Thus, the effect of the delay of the regulator is more significant for the shorter pressurization time plots, as can be seen from figure 12(c).

Figure 12(f) provides a comparison of the experiment and model mean speed according to the pressurization time for 5 kg weight. The experiment plot was not directly obtained from the experiment, but instead calculated by dividing the experimental period of the cycle shown in figure 12(d) from the experimental mean stroke per cycle shown in figure 12(e). As the model predicts the stroke to be larger and the period to be shorter, the error sums up to a maximum of 11%. Although there are substantial offsets, the general trend of the model fits well.
5.4. Clutch modes
Figure 13(a) shows the force-elongation profiles of the RIPA in the rigid and the soft clutch modes under absolute pressure levels of 200 kPa and 500 kPa. The RIPA showed a stiffer response in the rigid clutch mode, allowing much smaller displacement against external force. Figure 5(b) compares the equivalent stiffness values, defined as the external force divided by the displacement. The rigid mode showed the highest stiffness, and the stiffness of the soft modes decreased under the lower pressures. The soft clutch modes represent the case of conventional PAMs since the rack was connected to the PAM in series, as shown in figure 5(b). Thus, the RIPA can maintain its position with robustness against external disturbances compared to conventional PAMs by utilizing the rigid mode when necessary. Furthermore, the stiffness of the RIPA can be controlled by changing the input pressure in the soft mode. The small displacement in the rigid mode was caused by the elongation of the flexible rack itself. Therefore, the robustness of the RIPA under the rigid mode can be further increased if a stiffer material is used for the rack.

6. Conclusion
Based on the inspiration from the sarcomere contraction mechanism of biological muscles, this study proposes a new type of a soft linear actuator, a ratchet-integrated pneumatic actuator (RIPA), which has a limitless stroke length in theory. While maintaining the advantages of PAMs discussed in section 1, a RIPA can generate strokes independent from loads, maintain its length against unexpected mechanical disturbances, and be controlled with a relatively simple hardware and software system.

The analytic models of the stroke and the period per cycle were developed from the static force equilibrium and the Bernoulli equation for compressible fluids. Then, experiments were conducted to verify the mechanism and the models. The result showed that the accumulation of strokes during contraction was successful, while the relaxation required further improvement. The model predicted the general trend of the stroke and the period per cycle successfully with small errors.

One of the immediate areas of future work is the bundling of multiple RIPAs. While this concept has been studied with multiple PAMs [26], RIPAs have several advantages when bundled together. Since the cross-section of the flexible rack is extremely small, multiple RIPAs can form one strong actuator like a biological muscle, which is a bundle of sarcomere, while still maintaining the compact form factor. Also, force applied to the bundle will be automatically distributed equally to each RIPA, since a RIPA under a smaller load will contract faster than the other RIPA under a larger force. Furthermore, bundled RIPAs can generate smoother motions than a single RIPA as if combined sarcomere contractions with different phases make smooth motions of biological muscles.

Further improvements are possible in several ways. First, the limited actuation force of the mini-bag actuator for the RIPA relaxation can be addressed by simply increasing the air pressure of the mini-bag actuators after structural reinforcement. Second, as many studies have proven the substantial benefits of integrating sensing modules to soft actuators [18, 27–30], similar designs can be made with a RIPA as well. If sensing modules are directly embedded to a RIPA similar to muscle proprioceptors, such as muscle spindles or Golgi-tendon organs [18], onboard measurement of displacement will be possible, which may be more accurate than the video analysis used in this work (stacks.iop.org/BB/15/036011/mmedia). Third, reducing the interval of the teeth of the rack and selecting a stronger material for the ratchet system will increase the maximum load of a RIPA. Both are equally important since the maximum load is determined by both the failure of the ratchet system and the load that the base PAM can lift up until a single step of the flexible rack. The reduced interval of the teeth will also increase the resolution of the displacement. Fourth, as the length of the flexible rack increases, the importance of installing a reel mechanism to wind and store the extruded flexible rack from contraction will rise since it will eliminate the detrimental influence of the extruded rack and help the RIPA keep its compact form factor. Fifth, control strategies can be further developed with the help of the feedback from the integrated sensors. Finally, attempts to integrate RIPAs with a robotic system to demonstrate the advantage of large stroke and high force actuation are possible. RIPAs are expected to be particularly useful in wearable robotic devices for their soft, lightweight, compact, and compliant features that conventional rigid actuators with similar actuation performance are not able to achieve. Moreover, the unique function of a RIPA that can quickly switch the clutch modes will play an essential role in wearable robots. The soft mode provides the structural compliance of the robot that allows the existing degrees of freedom of the wearer as well as the absorption of external impacts, increasing the user’s safety. During the rigid mode, the robot can hold a load and lock its position without continuously applying air pressure, increasing both the load-bearing capacity and energy efficiency.

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ORCID iDs

Hyun Sung Cho  https://orcid.org/0000-0002-6451-4698
Yong-Lae Park  https://orcid.org/0000-0002-2491-2114

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