https://doi.org/10.20965/jrm.2016.p0226

Paper:

Study on a Pneumatically Actuated Robot for Simulating Evolutionary Developmental Process of Musculoskeletal Structures

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[Received April 2, 2015; accepted February 22, 2016]

Under the effects of surroundings such as gravitational force, ambient temperature, and chemical substances, each animal has acquired an optimized body structure through its evolution. For example, vertebrate land animals have a sophisticated musculoskeletal structure including not only monoarticular muscles but also multiarticular muscles to support their weight against gravitational force. Many researchers have developed musculoskeletal robots with a biarticular muscle mechanism that enables them to execute physical tasks similar to the mimicked animal. However, the developmental process of the musculoskeletal structure has not been examined in detail in past studies. In this study, we developed a musculoskeletal robot with redundant air cylinders to investigate the developmental process of the body structure of the animal. We proposed a switching mechanism between several muscle structures called the actuator network system (ANS). In the ANS, the selection of mutually interconnected, simultaneously activated air cylinders is changed by switching the interconnections. The experimental results indicate that by changing the connection of the cylinders and the inner pressure of the connected cylinders, i.e., the strength of the connection, the response of the robot to external forces can be modified, thus demonstrating the feasibility of our approach.

Keywords: actuator network system, evolutionary robotics, multiarticular muscle, musculoskeletal robot

1. Introduction

It is believed that the anatomical structures of living organisms have gained the ability to flexibly and rapidly move in an efficient manner by acquiring diverse functions with their evolution over time. As a result, the morphologies of living organisms today have become highly refined, enabling them to adapt to diverse, complex environments and survive [1, 2].

An important step in the evolution of the anatomical structures of living organisms is the acquisition of musculoskeletal structures by land animals that were quite different from those of underwater animals. Because of their different habitats, underwater and land animals developed entirely different locomotive modes. When animals emerged from the ocean and began living on land, it became necessary for them to acquire legs and musculoskeletal structures that enabled them to support their weight against gravity; thus, they acquired an anatomical structure that was more complex and refined than that of fish. Specifically, land animals drive multiple skeletal muscles simultaneously, and developed and made effective use of multiarticular muscles, which impose constraints on the movement of multiple joints [3, 4].

Researchers in biomimetic robotics have actively studied the functions of the anatomical structures of living organisms that have superior environmentally adaptive properties by simulating these structures or applying them to man-made structures [5]. In particular, robots equipped with biarticular muscles have been used to study the postural stability of the end effectors or functions to control the output or adjust the response [6–9]. In studies on leg-type robots, various applications have been developed such as the realization of stable continuous jumps through appropriate adjustment of the stiffness or its direction at the leg end [10, 11]. With these robots, the major thrust has been to simulate as closely as possible the refined anatomical structures of actual living organisms. As such, a top-down approach has been adopted in developing the robot's structure, which make it difficult for the robots to operate in environments other than the presumed ones. In contrast, focusing on the process in which anatomical structures evolved, the present authors adopt a bottom-up approach to modify the robot's behavior and aim to develop a robot capable of flexibly adapting to diverse environments by allowing it to change its structure.

Thus, the objective of this study is to develop a robot that simulates the evolutionary development of the musculoskeletal structure, which is considered to have undergone drastic changes in the presence of gravity. In particular, to examine the mechanism by which the structure of mono- and multiarticular muscles developed, we propose an actuator network system (ANS), which allows one to simultaneously move multiple joints by changing the interconnecting structure among multiple air cylinders in the drive system of a pneumatic robot, and thus design structures similar to multiarticular muscles. To examine the self-organizing structural development of the drive system of a robot based on an ANS, we have developed a musculoskeletal robot with a redundant structure driven by multiple air cylinders [12, 13].

In this paper, we report two findings regarding the response of the developed musculoskeletal robot against an external force. One is the response when the interconnecting structure of the air cylinders driving the joints and the internal pressures of the interconnected air cylinders were changed. The strength of the interconnection (i.e., the force transmitted between joints) can be increased by increasing the internal pressure of the interconnecting air cylinders. The other finding is the response when the external force was varied. Because multiarticular muscles transmit forces between joints and serve to interlink them, our analysis focuses on the changes in the joint angles. From these experiments, we verify whether one can simulate a biarticular muscle that simultaneously moves two joints using a tube to connect two air cylinders that are each provided to drive a separate joint.

The paper is composed in the following manner. In Section 2, we review the classification of skeletal muscles of living organisms and describe the proposed ANS and developed musculoskeletal robot. In Section 3, we present and discuss the results of two experiments on the responses of the developed robot against an external force. In Section 4, we provide our conclusions as well as plans for future investigations.

2. Musculoskeletal Robot

The anatomical structure of living organisms consists of the skeletal system composed of bones that provide support, joints that connect the bones, cartilage, and ligaments, and the muscular system, which is connected to the skeletal system and composed of muscles and tendons that serve to flex or extend the joints [3]. The flexible movements of a living organism are made possible by the hard skeleton, which resists external forces, and the muscles, which move flexibly. This mechanism is quite different from the structure of shaft-driven robots.

2.1. Classification of Skeletal Muscles of Living Organisms

The skeletal muscles that drive joints are connected to the skeleton at the ends (origin and insertion) and can be classified into mono- and multiarticular muscles depending on the number of joints between the ends (see **Fig. 1**).

Monoarticular muscles are muscles that drive a single joint. These muscles are also called agonists because they serve a central role in flexing or extending the joint that lies between their origin and insertion. These muscles are found around the joints of not only land animals but all living organisms that have a skeleton.

Multiarticular muscles, which include biarticular muscles, are muscles that connect bones that are separated by multiple joints. Because there are multiple joints between its origin and insertion, the motion of a single multiarticular muscle simultaneously affects all of these joints to create a diverse range of behavior. When a multiarticular muscle is contracted simultaneously with a monoarticular muscle, in addition to flexing or extending a joint, it structurally moves the other joints it spans by maintaining its muscle length to create a type of parallel link structure.

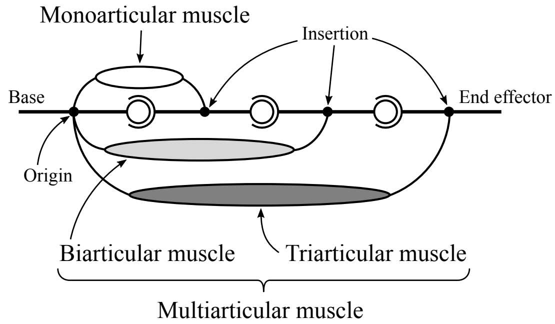


Fig. 1. Classification of the skeletal muscles.

To efficiently move the musculoskeletal system, which is composed of these different types of muscles, living organisms are endowed with what is known as muscle synergy as a mechanism to simultaneously control multiple muscles. It is thought that the body, which has a complex structure, can be controlled more easily by moving multiple muscles with a single control signal than by controlling all the muscles independently.

Furthermore, it has been observed that multiarticular muscles have interesting control properties and perform multiple functions [3]. One such property is that a musculoskeletal model with biarticular muscles is sometimes able to adjust the direction of the force exerted to the environment by the end effector, unlike a model with monoarticular muscles. This property has been examined in detail by computing the stiffness ellipse of the end effector [3]. By taking advantage of this property, one can make a robot stand up or perform consecutive jumps in a stable manner [4].

Biarticular muscles, which are a type of multiarticular muscle, interconnect two joints and place constraints on their degrees of freedom. It is therefore possible to adjust the response of the biarticular muscle to external forces by varying its viscoelasticity, thereby extending the computational possibilities of the anatomical structure or applying morphological computing [5]. Furthermore, allowing the anatomical structure to perform local responses against external forces on its own can reduce the information processing load on the brain, which serves as the controller, and allow diverse responses to be executed even with a slow control cycle.

For the above reasons, many biomimetic musculoskeletal robots possess structures similar to that of the biarticular muscle. In such robots, the goal is to make use of the functions of the biarticular muscle in a top-down manner, and the structures of the living organisms they are in-

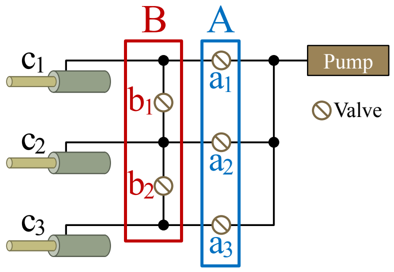


Fig. 2. Air flow diagram of the ANS for self-organizing robotic musculoskeletal system.

tended to mimic are copied in their original forms. Thus, in the present study, we employ a musculoskeletal robot that consists only of a collection of multiple joints and monoarticular muscles that move these joints and whose individual parts are not assigned any special functions. The goal is to develop a bottom-up method by which the robot can acquire a musculoskeletal structure that includes self-optimized multiarticular muscles through an evolutionary process in which it is affected by the environment and given tasks.

2.2. Actuator Network System

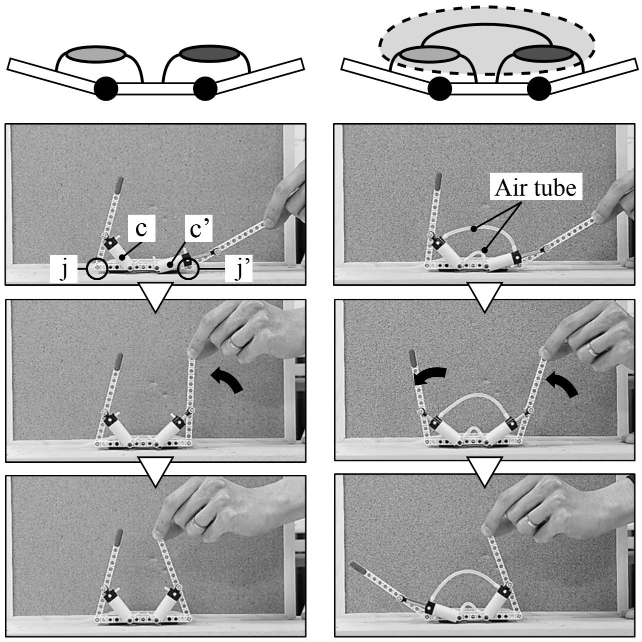
We describe the system configuration of a musculoskeletal robot that consists only of monoarticular muscles and has redundant degrees of freedom, which are necessary to realize (through evolutionary computation) a mechanism that allows the robot to acquire a structure that includes multiarticular muscles. In this study, multiarticular muscles are formed by pneumatically interconnecting multiple air cylinders by tubes to constrain the movements between joints. In other words, the robot is designed such that each joint is installed with multiple air cylinders, and it is able to acquire a structure with multiarticular muscles by switching the interconnecting structure among the air cylinders. A schematic diagram of the control system of air cylinders is presented in **Fig. 2**.

2.2.1. Muscle Synergy

In **Fig. 2**, when multiple valves belonging to group A are simultaneously opened, the air cylinders connected to the opened valves will simultaneously flex or extend. For example, if a_1 and a_2 are controlled such that they always open or close simultaneously, c_1 and c_2 can be considered to be in muscle synergy [14]. By identifying certain combinations of air cylinders that can be driven simultaneously under the given environment or task, one can extract muscle synergies and reduce the order of the control signals.

2.2.2. Multiarticular Muscles

A multiarticular muscle mechanism [15] can be constructed by pneumatically interconnecting the ports of multiple air cylinders using tubes or valves. Specifically, when valve b_1 in **Fig. 2** is opened, the air chambers of air



(i) Without connection (Monoarticular muscles)
(ii) With connection (Biarticular muscle)

Fig. 3. Comparison of motions indeed by 2 air cylinders with and without mutually inter-connection.

cylinders c_1 and c_2 will be interconnected. In this state, not only is it possible to inject air into or evacuate c_1 and c_2 to simultaneously drive the cylinders by opening either valve a_1 or a_2; however, by closing both a_1 and a_2, it is also possible to have the external force acting on c_1 affect c_2 as well. Because external forces can be transmitted between joints in this manner, multiple air cylinders can be made to behave as a single multiarticular muscle by interconnecting them pneumatically. In this study, when a force acting on a joint affects another joint via a physically connected actuator, we shall call the connected actuator a multiarticular muscle.

Figures 3(i) and **(ii)** present examples of joint movements when the air cylinders are not and are interconnected, respectively. In **Fig. 3(ii)**, when the air cylinders are interconnected, when one of the air cylinders c' is retracted by an external force, the other one c will be extended, such that the two joints j and j' move simultaneously. In **Fig. 3(i)**, when the air cylinders are not interconnected, the movement of one joint will not be transmitted to the other one.

Muscle synergy has been employed for robotic control in previous studies [16]. By selecting certain combinations of valves to be opened or closed, however, the present system not only achieves muscle synergy but also allows one to use the biarticular muscle structure to introduce changes to the robotic structure.

2.3. Musculoskeletal Robot Driven by Redundant Actuators

Figure 4 shows the developed musculoskeletal robot. The robot arm consists of four links. To allow the joints

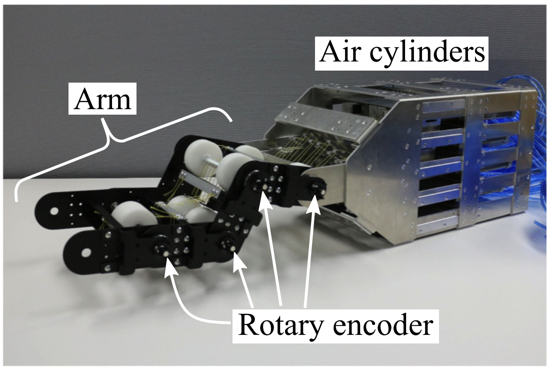


Fig. 4. The musculoskeletal robot with redundant air cylinders.

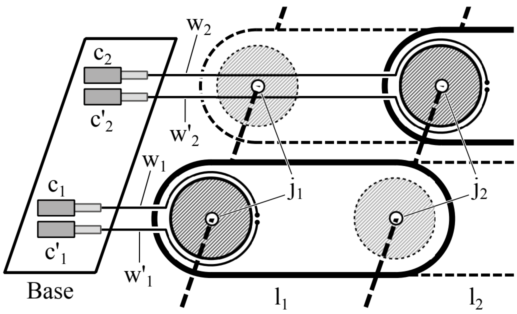


Fig. 5. The tendon driven system with Kevlar cords.

to flex and extend, each joint was installed with four pairs, with each pair consisting of two antagonistic air cylinders (CJ2B16-75, SMC) (a total of 32 air cylinders for four joints). To reduce the weight of the movable part of the robot arm, the heavy air cylinders were placed at the base of the robot, and a tendon drive was employed in which the joints were driven by Kevlar cords. Each joint was installed with an absolute rotary encoder (AEAT-6012, Avago Technologies), and the joint angles were recorded via microcontrollers (mbed[1]).

Figure 5 shows the configuration of the tendon drive system using Kevlar cords. The proximal joint j_1 of link l_1 is driven by air cylinders c_1 and c'_1, which are housed in the base, via Kevlar cords w_1 and w'_1 affixed to the pulley installed at j_1. The air cylinders c_1 and c'_1 are antagonistically arranged to flex joint j_1 in opposite directions. The Kevlar cords that drive the distal joint are relayed at the rotational center of the proximal joint and connect to the pulley at the driven joint. In this manner, the path length remains constant regardless of the angle (attitude) of the proximal joint, and the joint is driven by the corresponding air cylinder unaffected by other joints if we can neglect friction. Because the aim of this study is to realize a wide range of robotic behaviors using the ANS to change the interactions among joints, it is important to secure a diverse range of possible interconnecting structures. To this end, a redundant number of air cylinders were installed in parallel to each joint, which allows one to produce various interconnections, such as simultaneous multiple interconnections including the same joint, as in interconnecting j_1 and j_2 and interconnecting j_1 and j_3 simultaneously.

1. http://mbed.org/ [Accessed March 31, 2016]

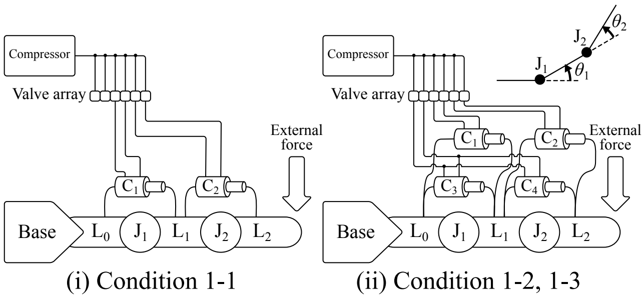


Fig. 6. The system configurations for the experiment 1.

3. Experiments

Two experiments were performed to verify whether air cylinders pneumatically interconnected by tubes behave as biarticular muscles.

To simplify the experiment, the two joints closer to the arm base were fixed such that they could not rotate, and the remaining two joints were used in the experiment. The musculoskeletal robot was positioned to make the moveable plane vertical; when air was supplied to the two air cylinders (C_1 and C_2) serving as monoarticular muscles at the upper part of the arm, the arm assumed a horizontal position. Because double-acting air cylinders are used, it is possible to arbitrarily set the position of the moving member by varying the supply of air in the two air chambers. Setting the initial condition in this manner, a falling object was made to collide with the tip of the arm, and the changes in the behavior of the arm due to this vertical impact were compared for different interconnections of air cylinders.

3.1. Experiment 1: Responses when Interconnecting Structure and Internal Pressure were Changed

Figure 6 shows the system configurations of the experiment. The following three conditions were compared. Under condition 1-1, the behavior of the arm was maintained using two air cylinders only. Under conditions 1-2 and 1-3, a pair of pneumatically interconnected air cylinders (C_3 and C_4) were used in addition to those used under condition 1-1. Under condition 1-3, the internal pressures of C_3 and C_4 were higher than those under condition 1-2. The internal pressures of air cylinders C_1, C_2, C_3, and C_4 are presented in **Table 1**, where the retraction- and extension-side pressures of air cylinder C_i are denoted $P^{\alpha}_{C_i}$ and $P^{\beta}_{C_i}$ $(i = 1, 2, 3, 4)$, respectively. The weight of the falling object was 313 g.

As illustrated in **Fig. 6**, the links are denoted L_0, L_1, and L_2, and the joints J_1 and J_2 form the base of the arm. L_0 is rigidly attached to the base in **Fig. 6**. The angles of

Table 1. Inner pressure of each cylinder (MPaG).

Condition 1-1						
Trial	$P_{C_1}^{\alpha}$	$P_{C_1}^{\beta}$	$P_{C_2}^{\alpha}$	$P_{C_2}^{\beta}$	P_{C_3,C_4}^{α}	P_{C_3,C_4}^{β}
1	0.249	0.162	0.174	0.133	–	–
2	0.245	0.164	0.172	0.135	–	–
3	0.244	0.165	0.171	0.136	–	–

Condition 1-2						
Trial	$P_{C_1}^{\alpha}$	$P_{C_1}^{\beta}$	$P_{C_2}^{\alpha}$	$P_{C_2}^{\beta}$	P_{C_3,C_4}^{α}	P_{C_3,C_4}^{β}
1	0.249	0.160	0.176	0.132	0.160	0.124
2	0.253	0.156	0.173	0.134	0.163	0.119
3	0.250	0.158	0.171	0.135	0.161	0.121

Condition 1-3						
Trial	$P_{C_1}^{\alpha}$	$P_{C_1}^{\beta}$	$P_{C_2}^{\alpha}$	$P_{C_2}^{\beta}$	P_{C_3,C_4}^{α}	P_{C_3,C_4}^{β}
1	0.249	0.158	0.174	0.132	0.592	0.507
2	0.252	0.155	0.175	0.131	0.588	0.507
3	0.250	0.156	0.176	0.130	0.588	0.502

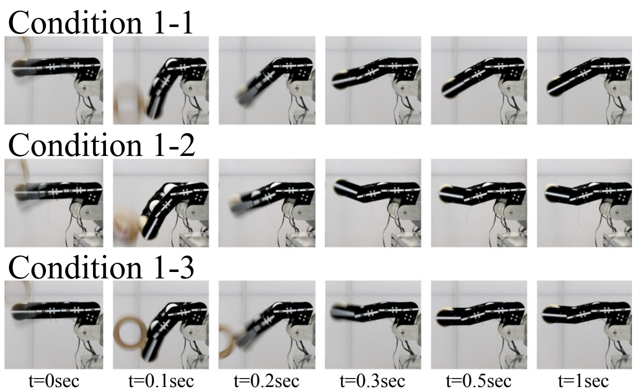
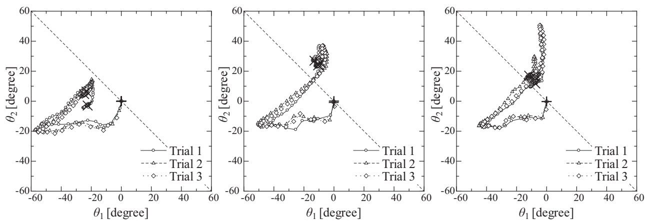


Fig. 7. Comparisons of responses to the external force.

L_1 relative to L_0 and L_2 relative to L_1 are denoted θ_1 and θ_2, respectively.

The changes in the behavior of the arm under the different conditions are shown in **Fig. 7**, and changes in the joint angles are shown in **Fig. 8**, where the abscissa and ordinate represent θ_1 and θ_2, respectively. In the initial behavior, θ_1 and θ_2 are both zero (indicated by the $+$ mark in **Fig. 8**). Under condition 1-1, θ_1 and θ_2 were both displaced in the negative direction when the vertically downward external force acted on the arm tip. Under conditions 1-2 and 1-3, the air cylinder driving J_1 was extended when θ_1 was negatively displaced, which caused the pneumatically interconnected air cylinder driving J_2 to retract, thus displacing θ_2 in the positive direction. As a result, the final positions of the change in joint angle (indicated by $\times$ in **Fig. 8**) are closer to the line $\theta_2 = -\theta_1$ under conditions 1-2 and 1-3 than under condition 1-1. Furthermore, the final position is closer to the line $\theta_2 = -\theta_1$ under condition 1-3 than under condition 1-2. This change resulted in making L_2 assume a more horizontal behavior.

As these results demonstrate, an effect tending to maintain L_2 in a horizontal behavior was achieved by installing pneumatically interconnected air cylinders. This function is also observed in musculoskeletal structures that contain biarticular muscles, demonstrating that the proposed interconnections between air cylinders is able to recreate the function of the biarticular muscle. The results also demonstrate that the interconnection can be strengthened by increasing the internal pressures of the pneumatically interconnected air cylinders.



(i) Condition 1 (ii) Condition 2 (iii) Condition 3

Fig. 8. Changes in joint angle due to application of external force (abscissa: θ_1, ordinate: θ_2).

Table 2. Conditions of experiment 2.

		Inter-connection	
		Without	With
Weight of the object	400 g	Condition 2-1	Condition 2-2
	550 g	Condition 2-3	Condition 2-4

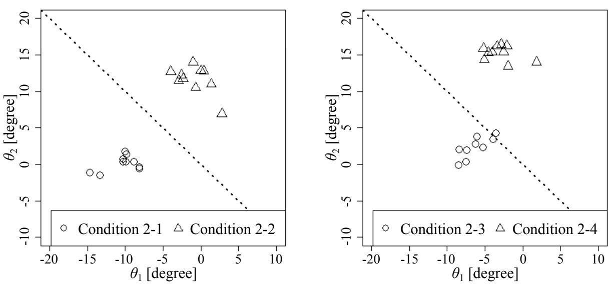
3.2. Experiment 2: Responses when the External Force was Varied

In this experiment, the responses when the magnitude of the external force was varied were measured. The following four conditions were compared (**Table 2**).

Under conditions 2-1 and 2-3, the air cylinders were arranged as under condition 1-1, and the behavior was maintained by applying the same respective internal pressures to the air chambers. Under conditions 2-2 and 2-4, the air cylinders were arranged as under condition 1-3 using the same respective internal pressures to the air chambers as the initial conditions. The distributions of final positions in the changes in the joint angle of the arm for the different conditions are presented in **Fig. 9**.

When the distances between the final positions under conditions 2-1 and 2-2 and the line $\theta_2 = -\theta_1$ are compared, we see that the median values are not very different. When the results of conditions 2-3 and 2-1 are compared, we see that the final positions of the former converge to the small displacements of θ_1 and θ_2, reducing their distance to the line $\theta_2 = -\theta_1$. Under condition 2-2, θ_2 is considerably displaced in the positive direction, which resulted in increasing the distance to the line $\theta_2 = -\theta_1$. This tendency was more pronounced under condition 2-4, which resulted in a greater distance between the final position and the line $\theta_2 = -\theta_1$.

In the musculoskeletal robot employed in the experiments, only air cylinders that pull the links upward were



(i) Condition 2-1, 2-2 (ii) Condition 2-3, 2-4

Fig. 9. Changes in joint angle due to application of external force (abscissa: θ_1, ordinate: θ_2).

installed. Under this state, when the external force acts on the end effector and causes θ_1 to change in the negative direction, C_3 will be extended. As a result, C_4 is retracted, causing θ_2 to be displaced in the positive direction. L_2 will remain horizontal if the two cylinders are displaced by the same amount. However, the displacement of θ_1 also causes C_1, whose role is to maintain the behavior, to be extended. Because C_1 is not interconnected with another air cylinder, it behaves as an air spring to pull link L_1 upward. Because force is transmitted between C_3 and C_4 only when C_3 is extended, no interconnection effect occurs when θ_1 is displaced in the positive direction. Thus, the displacement of θ_1 in the positive direction leads to the results of conditions 2-2 and 2-4. Although the aim of the present study was to examine the effect of various conditions on the relative movements of joints, that is, their phase relationship, the robot came to a standstill without settling into a steady-state motion because of the energy loss due to friction. However, we assumed that the phase relationship between joints was preserved under the stopped condition and that the differences in the conditions were reflected in the behavior differences; therefore, our discussion mainly concerns the behavior of the robot after it had come to a stop.

3.3. Discussion

The experimental results indicate that by pneumatically interconnecting multiple air cylinders, force is transmitted among multiple joints such that they mutually affect one another. Thus, it was confirmed that interconnected air cylinders can be used to realize the type of behavior in which the movements between joints are constrained as in biarticular muscles in living bodies.

There are two major advantages when the ANS is employed to interconnect and simultaneously move air cylinders. One is that it is possible to change the behavior of the entire robot using interconnected air cylinders to provide constraints between joints, as in a biarticular muscle. In other words, we can expect to develop a system that is not only capable of responding to a wide range of external disturbances by selecting the appropriate interconnections but also adaptable to a dynamic environment by modifying the interconnecting structure according to the situation.

The other advantage is that the proposed system can provide a platform for discovering efficient patterns of interconnections and simultaneous motions based on an intelligent use of the intrinsic mechanical dynamics of the robot in which the interconnections and simultaneous motions of multiple actuators are dynamically switched. Mechanisms that drive the living body such as biarticular muscles and muscle synergy can be thought of as effective mechanisms for achieving diverse, robust adaptations to the environment. Therefore, by optimizing the ANS using an evolutionary algorithm or other means to discover efficient patterns, the possibility exists to realize robotic systems with flexible environmental adaptation capacities and complex structures similar to the bodies of living organisms, which are endowed with a high degree of freedom and capable of various movements by reducing the effective hierarchical level of control.

4. Conclusion

In this study, by recognizing that the evolutionary process is affected by the environment and tasks required of the organism and considering the effect of gravity on the musculoskeletal structure of living organisms, we developed a robotic system with multiple degrees of freedom and redundancies. As the drive system for the robot, we proposed the ANS, in which air cylinders interconnected by switched valves are used to simulate multiarticular muscles. Through an experiment in which the end effector of the robot was subjected to an external force, we were able to verify that the pneumatically interconnected air cylinders are capable of producing behavior similar to biarticular muscles.

Although an explicit model such as a kinematic model is not required for robotic control, a model that incorporates robotic knowledge remains necessary. However, it is difficult to incorporate a robotic model in advance because real spaces contain many obstacles and external disturbances; therefore, learning must occur using data acquired from the actual operation of the robot. A future topic of investigation will be to propose a method of designing the combinations of air cylinders to be interconnected and kinematically linked based on given tasks and to develop an adaptive control method capable of acquiring an environmentally adaptable anatomical structure in the form of a robot capable of forming a self-organizing structure for interconnecting air cylinders.

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Main Works:
• Y. Nakata et al., "Development of a Pneumatic-Electromagnetic Hybrid Linear Actuator with an Integrated Structure," Proc. of IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, pp. 6238-6243, 2015.

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Main Works:
• Y. Nakamura, T. Mori, M. Sato, and S. Ishii, "Reinforcement learning for a biped robot based on a CPG-actor-critic method," Neural Networks, Vol.20, Issue 6, pp. 723-735, 2007.

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