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A Study of Electromagnetic Actuator for Electro-pneumatic Driven Ventricular Assist Device

Min Woo Jung[1,4], Chang Mo Hwang[2,4], Gi Seok Jeong[1,4], Jung Soo Kang[1,4], Chi Bum Ahn[1,4], Kyung Hyun Kim[1,4], Jung Joo Lee[1,4], Yong Doo Park[2,4], Kyung Sun[1,2,3,4]

[1]Biomedical Engineering of Brain Korea 21 Program, Korea University, Seoul, Korea
[2]Biomedical Engineering, Korea University Medical College, Seoul, Korea
[3]Thoracic and Cardiovascular Surgery, Korea University Medical College, Seoul, Korea
[4]Korea Artificial Organ Center, Korea University, Seoul, Korea
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Abstract: An electromechanical type is the most useful mechanism in the various pumping mechanisms. It, however, requires a movement converting system including a ball screw, a helical cam, or a solenoid-beam spring, which makes the device complex and may lessen reliability. Thus, the authors have hypothesized that an electromagnetic actuator mechanism can eliminate the movement converting system and that thereby enhance the mechanical reliability and operative simplicity of an electro-pneumatic pump. The purpose of this study was to show a novel application of electromagnetic actuator mechanism in pulsatile pump and to provide preliminary data for further evaluations.
The electromagnetic actuator consists of stators with a single winding excitation coil and movers with a high energy density neodymium-iron-boron permanent magnet. A 0.5 mm diameter wire was used for the excitation coil, and 1000 turns were wound onto the stators core with parallel. A prototype of extracorporeal electro-pneumatic pump was constructed, and the pump performance tests were performed using a mock system to evaluate the efficiency of the electromagnetic actuator mechanism.
When forward and backward electric currents were supplied to the excitation coil, the mover effectively moved back and forth. The nominal stroke length of the actuator was 10 mm. The actuator dimension was 120 mm in diameter and 65 mm in height with a mass of 1.4 kg. The prototype pump unit was 150mm in diameter, 150mm in thickness and 4.5kg in weight. The maximum force output was 70N at input current of 4.5A and the maximum pump rate was 150 beats per minute. The maximum output was 2.0 L/minute at a rate of 80 bpm when the afterload was 100mmHg.
The electromagnetic actuator mechanism was successfully applied to construct the prototype of extracorporeal electro-pneumatic pump. The authors provide the above results as a preliminary data for further studies.

Key words: Electromagnetic mechanism, Actuator, Electro-pneumatic pump, Pulsatile, Electromechanical type

INTRODUCTION

A ventricular assist device (VAD) can be categorized into pulsatile or non-pulsatile according to the pattern of the flow generated by the pump [1-2]. Although there have been debates comparing the non-pulsatile versus pulsatile pumps and both have pros and cons, it has been agreed that the pulsatile blood flow is more physiologic and the most VADs approved by FDA are pulsatile [3-6].

The usual driving force of pulsatile pumps has been pneumatic or electric in type depending on the way of power application to the blood sacs [7]. Although pneumatic pumps have been popular due to simplicity so far, the main limitations are noise, difficulty in controllability, limitation of mobility due to an air compressor, and so on. Electric types are superior to pneumatic types with respect to the above issues. However, an electromechanical mechanism which is the most useful method in electric types needs to convert the circular motion of the motor into a linear motion and requires a movement converting system including a ball screw, a helical cam, or a solenoid-beam spring, which may limit the durability and reliability of the pump [8-10]. Thus, the authors have hypothesized that an electromagnetic actuator

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Corresponding Author : Kyung Sun, M.D., Ph.D.
Thoracic and Cardiovascular Surgery, Korea University Medical Center 126-1, Anam-dong 5-ga, Sungbuk-gu, Seoul 136-705, Korea (South)
Tel. +82-2-920-5559, Fax. +82-2-928-8793
E-mail. ksunmd@kumc.or.kr, ksunmd@korea.ac.kr

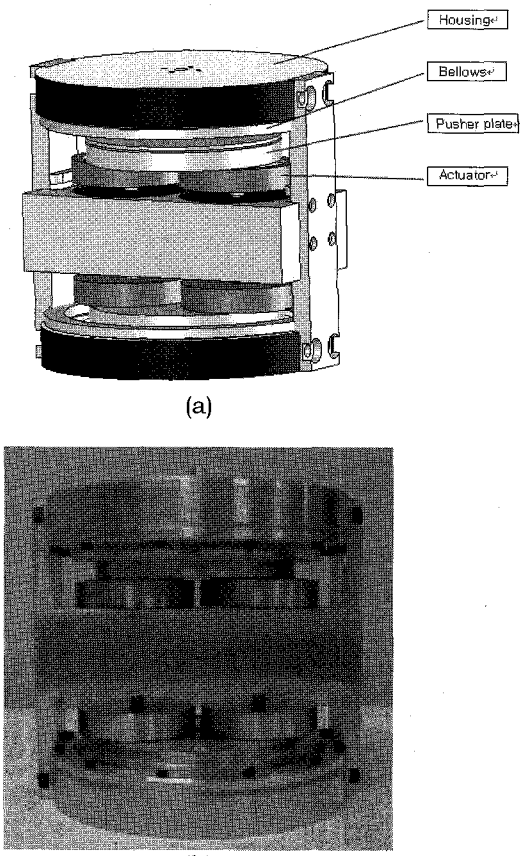
mechanism can eliminate the movement converting system and that thereby enhance the durability and mechanical reliability as well as the operative simplicity of an electro-pneumatic pump. The driving force consists of two parts; one is electromagnetic force compressing the air bellows and the other is pneumatic force transmitting the energy to compress the blood sacs.

The purpose of this study is not to develop the VAD, but to introduce a new conceptional actuator using electromagnetic actuator mechanism. In addition, it is significant to confirm the feasibility in pulsatile pump.

MATERIALS AND METHODS

Structures

The system is composed of two of each pump housing, bellows, pusher plate, and actuator. **[Figure 1]** The actuator consists of three sections; a stator, a mover and a guide.

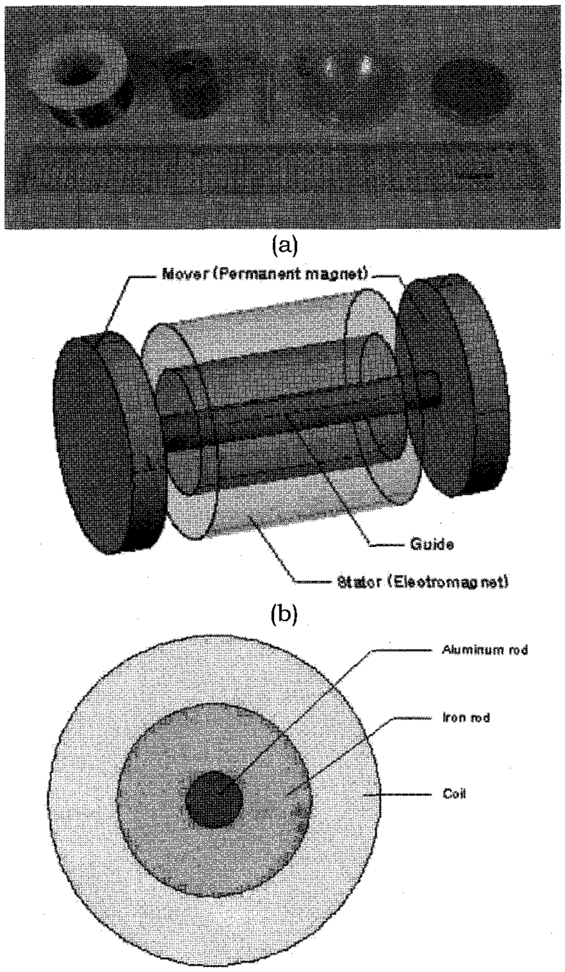


(a)

(b)

Fig. 1. Exterior view of the prototype pump unit using the electromagnetic actuator. The whole system comprises of two of each pump housing, bellows, pusher plate and actuator. (a) Schematic diagram of the pump unit. (b) Photograph of the pump unit.

[Figure 2] The stator is made of acetal which is an engineering plastic simple for part designing and applicability. As its main material, formaldehyde has crystalline resin which has excellent mechanical, chemical properties for long use. The stator is circular in shape with the inside filled with an iron rod of diameter 30mm. The outside is wounded with a 0.5mm solenoid to form a core. The inside of the iron rod has an aluminum rod and is connected to both sides of the support of the mover to support the up and down movement. The gap between the mover and the stator was kept at 10mm. The mover is made of a series of neodymium-iron-boron, a permanent magnet, with a diameter of 50mm. They are placed so that the like poles face each other. This will cause repulsion due to the electromagnetic forces. **Table 1** explains the properties of the actuator. In this research, two actuators were connected in a row to increase the electromagnetic force.



(a)

(b)

(c)

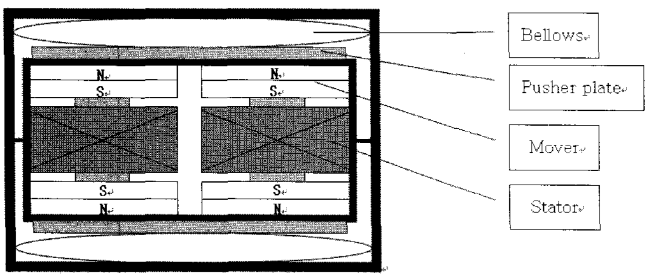
Fig. 2. (a) Disassembled view of the actuator. (b) Assembled view of the actuator. It consists of three parts: stator, mover and guide. (c) Sectional view of the stator. It consists of aluminum rod, iron rod, and coil.

Table 1. Specification of the Actuator

Diameter	60 mm
Core	30 mm
Guide	7 mm
Permanent magnet	50 mm
Height	75 mm
Weight	0.7 kg
Mover displacement	10 mm
Numbers of turn of coil	1000 / 0.5 mm

Principles

Figure 3 shows the movement of the actuator due to the electromagnetic forces. The top and bottom permanent magnets are placed N-S and S-N respectively to create repulsion. [**Figure 3(a)**] A coil is wound up on the iron core and current is flown so that an N-S pole is formed at both ends of the stator. [**Figure 3(b)**] An N-S-N-S-S-N magnetic pole is formed on the whole actuator generating attraction between the top permanent magnet and the stator and repulsion between the bottom permanent magnet and the stator causing the mover to move to the bottom. If the direction of the current is reversed an S-N pole forms at both ends of the stator, causing the mover to move to the top. [**Figure 3 (c)**] When forward and backward electric currents were supplied to the excitation coil, the mover continuously moved back and forth.



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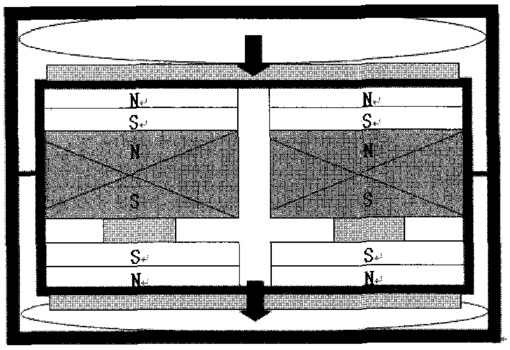

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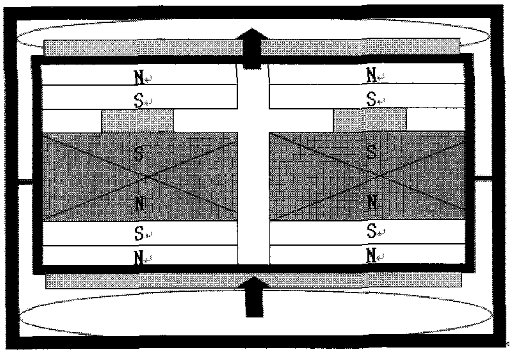

(c)

Fig. 3. Operation of the actuator. (a) Initial state which operates only permanent magnets. (b) Direction of actuator when N-S pole is formed at both ends of the core. (c) Direction of actuator when S-N pole is formed at both ends of the core.

Controller Design

The hardware is comprised of a voltage regulator, a control module and a motor driver. The input voltage of the voltage regulator is fed by the power supply. Its work is to supply a voltage to the controller module and driving module of 3.3V and 5V each. The CPU of the control module is a TMS320LF2406A (Texas Instruments, USA) DSP (Digital Signal Processor) which has feasible Timers, pulse width modulators (PWM) and 10 bit A/D converter. The driving module is comprised of an H-bridge circuit which controls the direction and the amount of the current flowing to the driver, therefore changing the polarity at both ends of the core periodically.

Pump Performance Experiments

The property of the actuator was measured by relationship between input voltage and input current. The values of the force output and input current were determined to check their relation. The *in vitro* performance of the pump was evaluated using a mock circulation. A maximum pump rate was measured with controls in the driving module. The changes in the pump output were measured with changes of the pump rate.

RESULTS

The relationship between input voltage and input current is shown in **Figure 4**. It was confirmed a heating effect when input voltage increased above 30V. **Figure 5** shows the change in force output with change in input current. A minimum input voltage of 10V and an input current of 1.2A were needed to operate the actuator. Therefore, the input power had to be at least 12W. The maximum force output was 70N at input current of 4.5A. The effect of the pump rate on the pump output is shown in **Figure 6**. A maximum pump rate was 150 beats per minute and there was no variation of input current with change in pump rate. The maximum pump output was 2.0 L/minute at a pump rate of 80 bpm when the afterload was 100mmHg. Above this rate, the pump output decreased. The input voltage was 25V and input current was 3A which was supplied from the power supply to the electric control.

DISCUSSION

A ventricular assist device is a mechanical circulatory support system that pumps the required amount of the blood to the body when the native heart is partially damaged. In the case of non-pulsatile pump, there is not considered as physiological. In addition, hemolysis caused by high-speed rotary motion of impeller is another concern of non-pulsatile pump [11-12]. However, a pulsatile pump generates physiologic pulsatile blood flow like that from the natural heart.

Considering the pathophysiologic characteristics of heart failure, a device being able to support both left and right ventricle (bi-ventricular ventricular assist device, BiVAD) seems to be reasonable. BiVAD can be applied for either intracorporeal or extracorporeal use depending on the condition of the heart. The intracorporeal BiVAD can be applied for chronic or end-stage heart failure and is considered as a heart-saving artificial heart especially when it comes as a single piece unit. The Korean artificial heart, AnyHeart (Biomedlab Co., Seoul, Korea) is an example [13]. The traditional total artificial heart such as Abiocor (Abiomed, Danvewrs, USA) is called as a heart-replacing artificial heart [14]. The extracorporeal BiVAD can be applied for both acute and chronic heart failures. Moreover, it also can be applied as LVAD, RVAD, or as an extracorporeal life system [15].

The newly developed actuator has used electromagnetic mechanism for extracorporeal biventricular assist. It uses the magnetic attraction and repulsion caused by the poles move the actuator. This prevents the rise of mechanical defects, and allows the control of the mover by altering current flowing through the core. It is a device which has a simpler structure and better reliability than present electro-mechanical pumps.

The prototype pump unit was 150mm in diameter, 150mm in thickness and 4.5kg in weight. The bellows generating air pressure was 120mm in diameter, and its volume was 210 ml. The pump operated back and forth when forward and backward electric current was supplied to the excitation coil. At that time, maximum nominal stroke length was 10mm. From the pump performance experiments, we confirmed a fact that the more input voltage increases, the more input current increases. **[Figure 4]** This linearity of input current is important to control the actuator. In addition, as the input current is increased, the intensity of the magnetic poles suspended at both ends of the core increases resulting in an increase in the force output. **[Figure 5]** However, power loss was observed due to heating effects since above 30V, and as a result, the decrease of input current from same voltage caused the reduction of force output. To solve this problem, we will supplement a cooling apparatus and build the actuator with a material more suitable for thermal conductivity.

Other results were obtained from the *in vitro* performance experiments. A maximum pump output of 2.0 L/minute was found when the pump rate was 80 bpm. **[Figure 6]** The reason why pump output was low is that pressure generated by electromagnetic force was low, and then blood sac was not operated to full-fill and full-ejection. We consider that actuator will augment pressure generation, and sufficient pressure will be created in the future as long as we make shielding equipment which prevents flux spill for the maximization of electromagnetic force. Besides, we will decrease the air gap in order to increase the attraction and repulsion of electromagnet. At this point in time, our research has focused on the verifying feasibility of a new actuator.

From this study, we confirmed that based on electromagnetic mechanism, actuator is not easy to control of movement velocity in a no load condition. However, it was prevented a phenomenon that actuator suddenly shifts with increasing pressure of pneumatic circuit due to displacement in state of connected bellows. In the future, we will detect the position of actuator using a gap sensor and will control current with displacement in order to observe the relationship between pneumatic pressure and driving power.

Only by using an electromagnetic mechanism, our pump could be made a simple operation of pulsatile pumps. If the electromagnetic force is improved, our pump would be available as extracorporeal BiVAD.

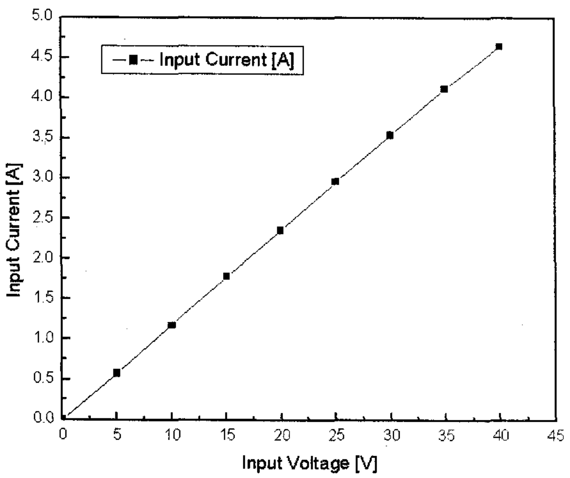

Fig. 4. Relationship between input voltage and input current.

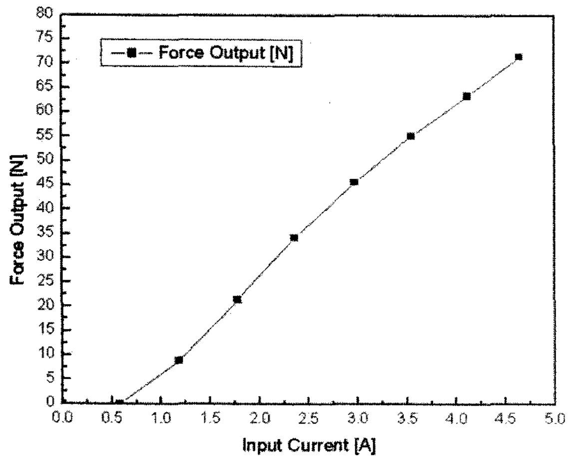

Fig. 5. The change in force output with change in input current.

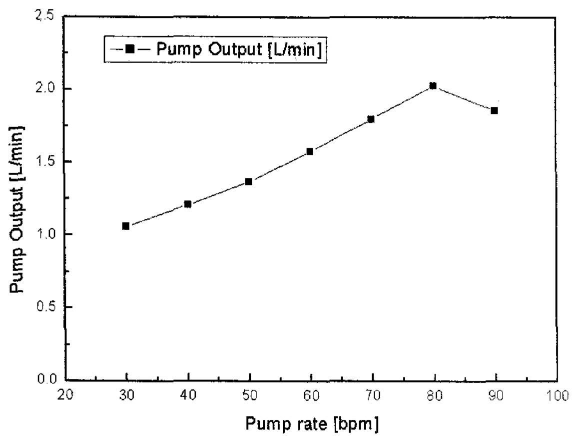

Fig. 6. The effect of the pump rate on the pump output of the *in vitro* experiment (afterload 100 mmHg).

CONCLUSION

A new electromagnetic actuator has been designed for a pulsatile blood pump. The system has been successfully actualized to construct the prototype of an extracorporeal electro-pneumatic biventricular assist device. The *in-vitro* pump performance test shows the positive potential for extended reliability and mechanical simplicity. The authors would like to provide the results as preliminary data for further studies.

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