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Investigation of Generative Contactile Force of Frog Muscle under Electrical Stimulation

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Recently, the microrobots powered by biological muscle actuators were proposed. Among the biological muscle actuators, frog muscle is well known as a good muscle actuator and has a large displacement, actuation forces and piezoelectric properties. Therefore, for the application of the biomimetic microrobot, this paper reports the electromechanical properties of frog muscle. First of all, the experimental setup has been established for measuring generative force of the frog muscle. Through the various electrical stimulating inputs to the frog muscle, we measured the contractile force of the frog muscle. From the measuring results, we found that the actuating contractile force responses of the frog muscle are determined by the amplitude, frequency, duty ratio, and wave form of the stimulation signal. This study will be beneficial for the development of the microrobot actuated by frog muscle.

Key Words : Frog Muscle, Biomimetic Microrobot, Electromechanical Property, Contractile Force, Micro Actuator

1. Introduction

Over the past two decades, novel concepts of the microrobot have been introduced (http://www.foresight.org ; Phee et al., 2002 ; Jung et al., 2003 ; Park et al., 2006). Because of the size limitation of the microrobot, however, the selection of the proper micro actuator is not easy and the realization and fabrication of the microrobot are also difficult. As a micro actuator, in general, the electrostatic, electromagnetic, pneumatic, piezoelectric and thermal actuators are mostly manufactured by MEMS (Micro Electro Mechanical System) fabrication procedures. These actuators have small size features and positioning accuracy but low efficiency and some limitation of the large sized external controller unit as the micro actuator for the microrobot.

Compared to the abovementioned artificial micro actuators, cell based actuators have been proposed and the miniature robot has been also introduced by Xi et al. (2004). The cell based actua-

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tor is fuelled by a simple glucose nutrient in physiological fluids as an energy source and transforms the chemical energy into mechanical energy. In the presented micro-robots (Xi et al., 2004), as a structural backbone, an arch of silicon 50 μm wide is used and a cord of rat cardiac muscle fibers has been grown. Contraction and relaxation of the cardiac muscle makes the arch bend and stretch to produce a crawling motion.

As an alternative, the biological muscle can be considered as an alternative solution for microrobot. For example, a swimming robot actuated by living frog muscle was fabricated and the locomotion tests are executed (Herr and Dennis, 2004). For the swimming robot, the frog muscles were cultured from the frog's leg and a ringer solution was used to surround each muscle. The frog muscle actuator of the swimming robot has not only high efficiency but also a simple controller. Therefore, this frog muscle actuator can be easily applied to the microrobot.

In order to adopt the frog muscle as the biological micro actuator, the electromechanical properties of the frog muscle should be analyzed. The piezoelectric properties of biological soft tissues were well reported (Shamos and Lavine, 1967; Hammer, 2002; Liu et al., 2005). However, these papers did not present the relation between the stimulating signal and the contractile force response of the frog muscle.

Therefore, for the application of the microrobot, this paper aims to analyze the contractile force of the frog muscle according to the stimulating signal. Based on an electromechanical test setup and sampling of the frog muscle, contractile force from the frog muscle will be measured on real time. Especially, the electromechanical properties of the frog muscle will be investigated under variation of the amplitude, frequency, duty ratio, and wave form of the stimulation signal. This report can give a guidance to design biological actuator using frog muscle for microrobot. The paper is organized as follows: In the following section, preparation method and experimental setup for the measurement of electromechanical properties will be explained. Section 3 will present the experimental results and discussions. Finally, concluding remarks will be drawn in section 4.

2. Methods

2.1 Preparation

According to procedures proposed by biomedical engineering laboratory, fresh flog muscles are extracted from living frog. The adult frog muscles are cultured with the Achilles tendon. The soft muscle tissue is fixed by the clamper in test bed. The soft muscle tissue and the test bed are immediately placed in small glass chamber filled with Ringer's solution after the muscles are explanted from the frog. The cultured frog muscle and the test bed are shown in Fig. 1. Ringer's solution is used in physiological experiments. It contains sodium, potassium, calcium chlorides, sodium hydrogen carbonate, glucose, and water. The composition of the Ringer's solution is illustrated in Table 1.

2.2 Electrical stimulation and contractile force measurement system

The overall schematic diagram for the stimulation and measurement is shown in Fig. 2. First, frog muscle is extracted from living frog and the frog muscle is clamped by the two clampers and

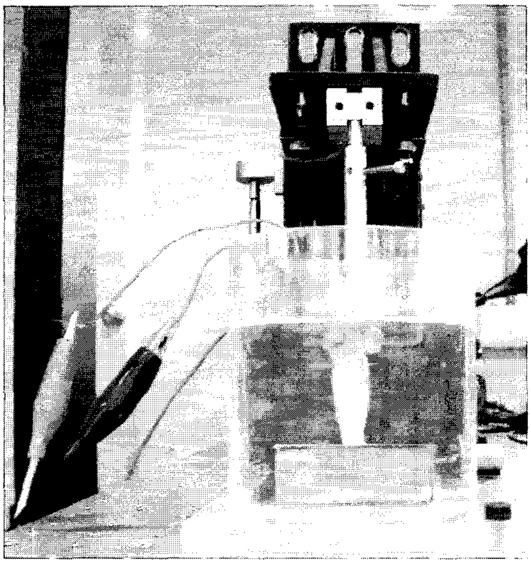

Fig. 1 Cultured frog muscle and test bed

immerged in the Ringer's solution. One clamp is fixed to the bottom and the other clamp is connected to the force transducer. As a force transducer for the measurement of the contractile force, the precision load cell (Model : GSO-1000 of Transducer technology Inc., Max. measurement force range : *1000 gf*) is used. The load cell is fixed with up-down precision manual stage which is used for the calibration of the neural position of the frog muscle. The contractile force signal from the load cell is amplified by the signal amplifier (Model : 2301A of VISHAY) and the amplified force signal is A/D converted through DAQ board (dSPACE) and filtered through a low-pass filter with cut-off frequency of 1000 Hz and recorded by Simulink (MATLAB).

Second, for the electrical stimulation of the frog muscle, the electrodes within the clampers are connected with the ends of the frog muscle. The stimulating signals with various patterns such as square, saw, and sinusoidal signal are generated using pulse generation module of Simulink (MATLAB) and applied through D/A function of DAQ board (dSPACE).

Table 1 Composition of Ringer's solution (The chemical container is for the one liter concentration solution)

Composition	Contents (g)
NaCl	3.799
KCl	0.056
$CaCl_2$	0.294
$NaHCO_3$	0.084
Glucose	10.000

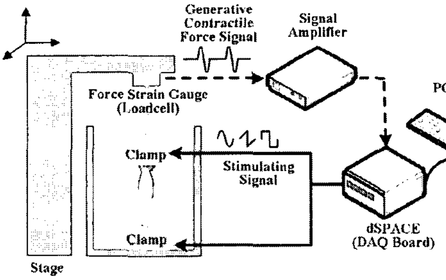

Fig. 2 Overall schematic diagrams for the stimulation and measurement (Solid line : Electrical stimulating sequence, Dotted line : Measurement sequence)

3. Experiments

For various electrical stimulating input signals, the contractile forces of the frog muscle are investigated and compared. First of all, we select the square wave as a stimulating signal. Generally, the square wave can be characterized by its duty ratio, amplitude and frequency. Therefore, the effects of the above parameters are examined. In addition, the other stimulating signals such as saw and sinusoidal wave are applied to the frog muscle and the contractile forces are measured and compared with other measurement results.

2.3 Effects of parameters in square wave

For the parametric study of the square wave, its duty ratio, amplitude, and frequency are changed. First, the duty cycle is changed as 5, 25, and 50% and the other parameters are fixed as the amplitude (2.0 Volt.) and the frequency (1 Hz). The measurement results of the contractile force are shown in Fig. 3. From the results, the effects of the duty ratio of the square wave are as follows :

(1) When the duty ratios are 25 and 50%, the contractile force responses appear at the raising and falling edge of the stimulating square wave. Generally, the contractile force at the raising edge

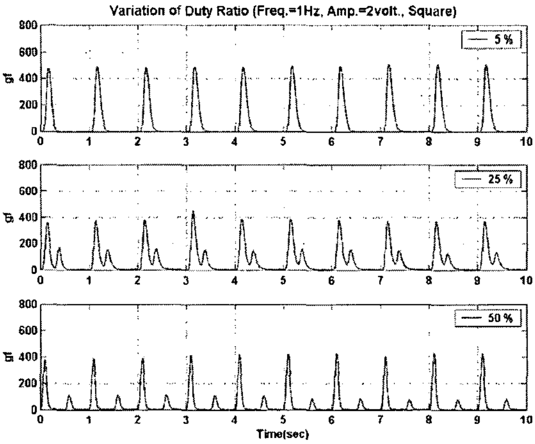

Fig. 3 Effect of the duty ratio in square stimulating wave (Frequency : 1 Hz, Amplitude : 2 Volt.)

is larger than that at the falling edge.

(2) On the other hand, when the duty ratio is 5%, the contractile force responses appear only at the raising edge of the stimulating square wave.

From the above study on the duty ratio of the square wave, 5% duty ratio is proper and applicable for the application of the microrobot.

Second, the amplitude of the square wave is switched to 1, 2, or 3 Volt. In these experiments, the duty ratio is chosen as 5%, which is selected in the above tests and the frequency is fixed as 1 Hz. The effects of the amplitude are shown in Fig. 4 and are concluded as follows :

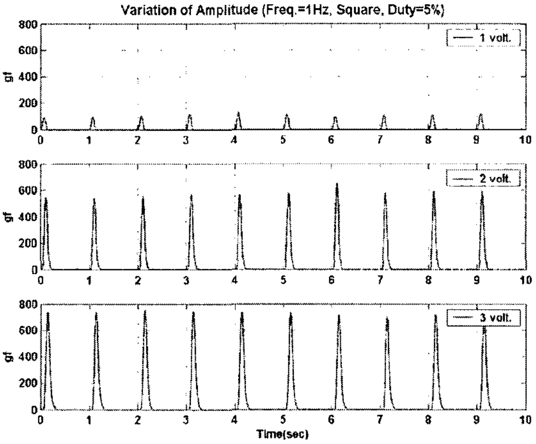

Fig. 4 Effect of the amplitude in square stimulating wave (Frequency : 1 Hz, Duty ratio : 5%)

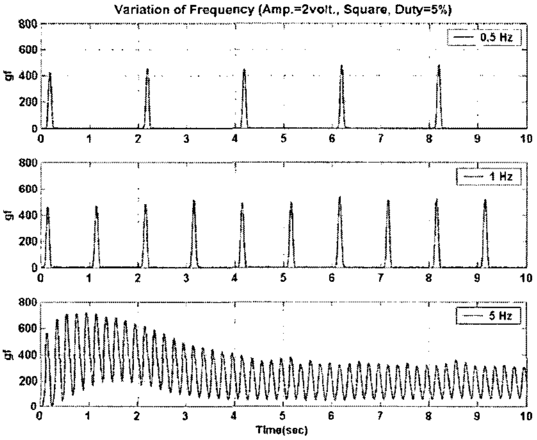

Fig. 5 Effect of the frequency in square stimulating wave (Amplitude : 2 Volt, Duty ratio : 5%)

(1) As the amplitude of the stimulating signal increases, the contractile force of the frog muscle also increases.

(2) From the other experiments, we can expect that there is a threshold voltage about 600 mV which the contractile response of the frog muscle does not appear.

Because the microrobot is generally operated by a battery, the actuating voltage below 3 Volt is appropriate.

Finally, the effect of the frequency of the square wave is tested. The frequency is changed as 0.5, 1.0, and 5.0 Hz. In addition, the duty ratio is set to be 5% and the amplitude 2 Volt. The experimental results of the frequency variation are shown in Fig. 5 and analyzed as follows :

(1) When the frequencies are 0.5 and 1 Hz, the contractile responses of the frog muscle are very similar to that of the previous tests.

(2) However, when the frequency reaches to 5 Hz, the contractile response shows a different trend. Owing to the fast stimulating input signal, the contractile response of the frog muscle is not completely restored and compressed.

(3) In addition, under the high frequency stimulating input signal, the fatigue phenomenon of the frog muscle is observed and it causes significant reduction of the contractile force.

Therefore, in order to keep stable contractile force of the frog muscle, the stimulating input signal with a high frequency should be excluded.

3.2 Comparison of wave form

For the comparison of the stimulating wave form, we select a sinusoidal and a saw signal. The stimulating signals have the amplitude of 2Volt and the frequency of 1 Hz. As a reference stimulating signal, the above examined square signal is selected and has the same amplitude and frequency and the duty ratio of 5%. The effects of the stimulating wave form are shown in Fig. 6 and are explained as follows :

(1) Compared to the results of the saw and the square inputs, the contractile force of the sinusoidal signal is too small. Therefore, we know

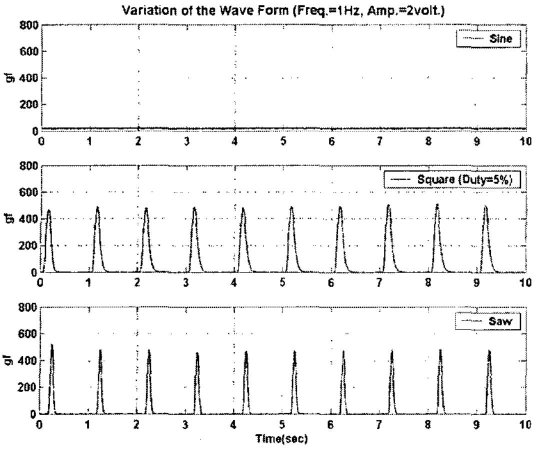

Fig. 6 Effect of the stimulating wave form (Frequency : 1 Hz, Amplitude : 2 Volt.)

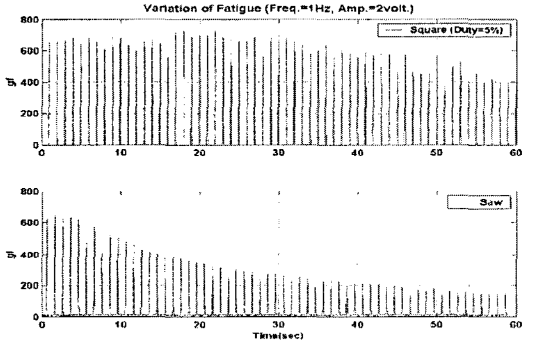

Fig. 7 Fatigue response of square and saw wave inputs (Frequency : 1 Hz, Amplitude : 2 Volt.)

that the frog muscle is effectively responded by the sudden change of the stimulating input.

(2) The response of the saw input is very similar to that of the square stimulating input. However, from the long stimulating results in Fig. 7, the contractile force due to the saw input shows fatigue phenomena and rapidly decreases. On the other hand, the contractile force due to the square input slowly decreases as time goes along. Consequently, compared to the saw input, the square stimulating input has advantages in the viewpoint of the generative force and the fatigue.

4. Conclusions

For the investigation of a contractile force of the frog muscle, the electrical stimulation and contractile force measurement system was developed and the generative contractile forces of the frog muscle under the various stimulating signals were measured. Especially, the effects of the parameters of the square signal were investigated and the contractile forces according to the stimulating wave form, such as saw and sinusoidal signal were compared. Based on parametric studies of the square stimulating signal, for the application of a microrobot, the duty ratio of the square input should be less than 25% and the frequency less than 5 Hz. In addition, the amplitude of the square input is proportional to the magnitude of the contractile force of the frog muscle. However, because the microrobot is generally operated by a battery, the actuating voltage below 3 Volt is appropriate. Through the comparison of the wave form of the stimulating signal, the contractile force response of the saw stimulating signal is very similar to that of square stimulating signal. But, the contractile force of the sinusoidal stimulating input is nearly zero. Finally, from the viewpoint of the fatigue phenomena, the square input signal shows better performance than the saw input signal. Consequently, the frog muscle can generate the contractile force up to 500 gf using the electrical stimulating signal of square wave form and the stimulating signals for the frog muscle were characterized and compared. This report can give a guidance to design biological actuator using frog muscle for the application of a microrobot.

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