

## Effects of Pulse Waveforms and Muscle Lengths on Muscle Force and Fatigue Resistance

**Song T<sup>1</sup>, Hwang SH<sup>1</sup>, Hyun BR<sup>1</sup>, Khang G<sup>1</sup>, Lee MS<sup>2</sup>, Lee BS<sup>2</sup>**

<sup>1</sup>Department of Biomedical Engineering, Kyung Hee University, Yongin-si, Korea

<sup>2</sup>National Rehabilitation Hospital, Seoul, Korea

tongjinsong@bcline.com

### Abstract

*We investigated contractile properties, force-generating capability and fatigue resistance, of quadriceps of 6 paraplegic patients and 7 healthy subjects. The knee extensor torque was monitored for more than 30 seconds during each stimulation session where 4 different waveforms were applied at 3 different knee angles for the patients. The result suggested that monophasic pulses could generate a higher torque with higher fatigue resistance than biphasic pulses at the cost of risks like skin irritation, when the muscle was submaximally stimulated. Also, the knee extensor showed the highest fatigue resistance at the optimal length when it was stimulated as well as voluntarily activated. More experiments are being conducted, however, to confirm this observation.*

### 1. INTRODUCTION

Functional electrical stimulation (FES) has been drawing much attraction for mobility recovery of plegic people since its practical application to footdrop [1]. The major reason was that mobility recovery by means of FES has many advantages over conventional orthotic devices, e.g., the user uses his/her own muscles, joints and metabolic energy.

In spite of such advantages, problems still need to be solved before easy application of FES to daily lives of the users. One of the major problems is insufficient understanding of muscle responses to electrical stimulation including fatigue. This is particularly true these days since various highly-sophisticated engineering techniques are available, such as digital control system design and signal processing, whereas few basic studies [2][3] have reported about, for instance, responses of a muscle to different electrical pulses at different stimulation conditions.

In this study, we investigated contractile properties, force-generating capability and fatigue resistance, of quadriceps of 6 paraplegic patients and 7 healthy subjects. The knee extensor torque was monitored for more than 30 seconds for each stimulation session where 4 different waveforms were applied at 3 different knee angles. This paper introduces our first-step experimental results.

### 2. METHODS

#### 2.1 Subject selection

Six incomplete paraplegic patients (age: 43.7±7.3 years) and 7 healthy subjects (age: 20.7±2.2 years) participated in this study. The patients were selected among the inpatients of the National Rehabilitation Hospital, Seoul, Korea, and the rehabilitation medicine team did medical examinations, such as the bone density examination, computerized tomography of the lower extremities, etc., to avoid any contraindication of FES. The healthy subjects were selected among the undergraduate and graduate students in the authors' department, and they were decided to have no medical problems by physical and mental examinations.

Each of them was given detailed explanation about every experimental procedure and any potential danger that could occur during experiments, such as skin irritation. All experiments were done with their written consents.

#### 2.2 Torque measurements and muscle stimulation

The subject was seated on a chair, developed by our research team, with the trunk at the upright position, and the knee angle was fixed at 3 different positions, 90°, 120° and 150° (90° and 150° in case of the healthy subjects). The fully extended position corresponds to 180°. A load cell (UB-K100, Jungsan, Inc., Seoul, Korea)

was used for measuring the force acting on the ankle when the knee extensor was stimulated. The free body diagram was applied to calculate the knee extensor torque.

A reference electrode was attached slightly proximal to the patella of each patient, and a stimulating surface electrode (5×9cm, Axelgaard, Fallbrook, CA) was positioned at the motor point of the quadriceps. The motor point was determined manually as the point that provided the maximum muscle contraction. Electrical stimulation was applied to both legs of the patients with the frequency fixed at 20Hz. The healthy subjects were trained and asked to fully activate the knee extensors without interference of the upper body.

### 2.3 Waveforms and stimulation conditions

Four different types of pulses were employed to investigate how the muscle torque and the muscle fatigue are affected by the waveform of the stimulation pulse: rectangular monophasic pulses ( $P_{mono}$ ), balanced biphasic pulses ( $P_{50\%}$ ), unbalanced biphasic pulses ( $P_{25\%}$ ), and one-period sinusoidal pulses ( $P_{sine}$ ), as shown in Fig. 1. The average power delivered by each constant-current pulse was kept constant for each subject, and only one stimulation was conducted per day in order to avoid any effect caused by previous simulations.

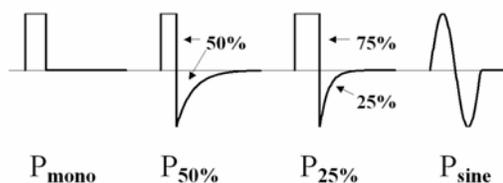


Figure 1. Four waveforms employed in this study

### 2.4 Data collection

The peak torque and the fatigue index, defined below, were measured and averaged for each subject. The paired t-tests were done to each pair of the measurement groups, e.g., torques generated by  $P_{mono}$  ( $T_{mono}$ ) and those by  $P_{sine}$  ( $T_{sine}$ ), with the level of significance at 0.05. In all torque measurements, the torque was normalized with respect to the initial (peak) value, and the results from different subjects were all averaged. Note that a low fatigue index indicates high fatigue resistance.

## 3. RESULTS AND DISCUSSION

As far as the waveform was concerned, we found  $T_{25\%} > T_{mono} > T_{50\%} \approx T_{sine}$  ( $p < 0.05$ ) (Fig. 2). Although  $T_{50\%}$  was slightly higher than  $T_{sine}$ , the difference was statistically not significant ( $0.23 < p < 0.29$ ). This was true regardless of the knee angle. The result was in agreement with [2][6][7] in that the threshold current of the monophasic pulse was lower than that of the biphasic pulse so that, given a submaximal activation level, the former could generate a relatively higher torque at the cost of potential risks such as skin irritation and/or discomfort [3]. Field-Fote et al. [8] reported an experimental results that a biphasic stimulation could produce an additive stimulation effect if the leading negative phase was long enough for the subthreshold in the  $Na^+$  conductance, contrary to our result. Recalling that the average power delivered by each pulse we kept constant for each subject. We can note that the leady negative phase of  $P_{50\%}$  was about 20% shorter than that of  $P_{mono}$ , and therefore the additive effect of the trailing positive phase, if any, might have been less than that of the continuous negative phase. Another finding was that  $T_{25\%}$  was always higher than  $T_{mono}$ . Although we cannot provide a full explanation about this to date, it can be noted that the average power delivered by each pulse was kept constant for each subject, and that consequently the pulse width of  $P_{25\%}$  was generally longer than  $P_{mono}$  by approximately 20% (see Fig. 1). Therefore, the rising phase of the muscle force was extended with  $P_{25\%}$ . Fig. 2 also confirmed that the knee joint torque was the lowest at 90° whereas the highest at 150°, but the difference between 120° and 150° was statistically not significant ( $0.2 < p < 0.35$ ), which implied that the optimal length of the quadriceps corresponded to the knee angle between 120° and 150°.

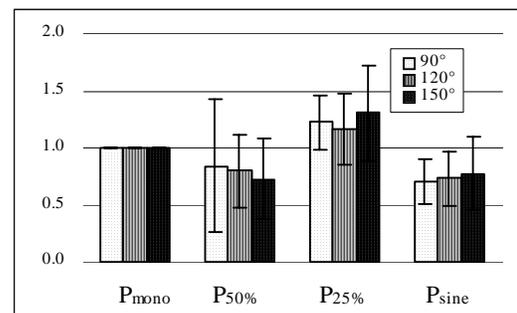


Figure 2. Peak torques generated by different waveforms, normalized with respect to that by  $P_{mono}$ , measured at 3 different knee angles

The mean value of the fatigue index was slightly higher with  $P_{50\%}$  and  $P_{sine}$  than with  $P_{25\%}$  and  $P_{mono}$ , though statistically not significant ( $p>0.06$ ), and the lowest at  $150^\circ$  of the knee angle and the highest at  $90^\circ$  regardless of the waveform ( $p<0.05$ ) (Fig. 3). It is to be noted that, around its optimal length, a stimulated muscle could generate the highest force with the highest fatigue resistance. The healthy subjects showed the same result, with the fatigue indices of  $26.4\pm 10.4\%$  and  $19.0\pm 8.3\%$  at  $90^\circ$  and  $150^\circ$ , respectively. This result, however, is contrary to [4] which reported that fatigue was bigger when the muscle length was shortened. They referred to a hypothesis suggested by [5], to account for their result, that the activation is decreased in short muscle lengths and high-frequency fatigue. However, though this hypothesis can explain why the maximum muscle force is low in short lengths, it does not necessarily explain why the muscle fatigues more in short lengths. This observation on the length dependence of the muscle fatigue, therefore, needs more in-depth research.

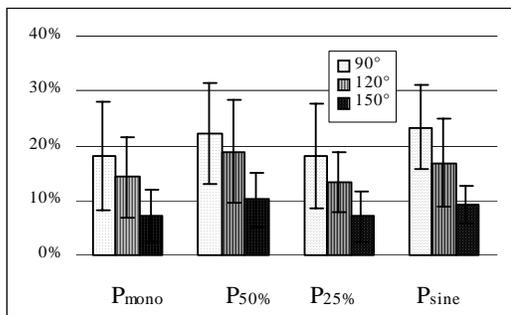


Figure 3. Fatigue indices (%) for different waveforms at 3 different knee angles

#### 4. CONCLUSIONS

We conducted an experimental study to investigate the effect of the waveform and the muscle length on the force-generating capability and the fatigue resistance. The result suggested that monophasic pulses could generate a higher torque with higher fatigue resistance than biphasic pulses, when the muscle was submaximally stimulated. Also, the knee extensor showed the highest fatigue resistance at the optimal length when it was stimulated as well as voluntarily activated.

More experiments are being conducted, however, to confirm this observation.

#### References

- [1] Liberson WT, Holmguest HJ, Scott D and Dow A, Functional electrotherapy: stimulation of the peroneal nerve synchronized with the swing phase of the gait in hemiplegic patients, *Arch Phys Med Rehab*, 42:101-105, 1961.
- [2] Gorman PH and Mortimer JT, The effect of stimulus parameters on the recruitment characteristics of direct nerve stimulation. *IEEE Trans Biomed Eng*, BME-30:407-414, 1983.
- [3] Baker LL, Bowman BR and McNeal DR, Effects of waveform on comfort during neuromuscular electrical stimulation, *Clin Orthop Rel Res*, 233:75-85, 1988.
- [4] Rassier DE, The effects of length on fatigue and twitch potentiation in human skeletal muscle, *Clin Physiol*, 6:474-482, 2000.
- [5] Gauthier AP, Faltus RE, McKlem PT and Bellemare F, Effects of fatigue on the length-tetanic force relationship of the rat diaphragm, *J Appl Physiol*, 74:326-332, 1993.
- [6] Honert CVD and Mortimer JT, The response of the myelinated nerve fiber to short duration biphasic stimulating current, *Ann Biomed Eng*, 7:117-125, 1979.
- [7] Reilly JP, Applied bioelectricity, New York, Springer-Verlag:133-134, 1998.
- [8] Field-Fote EC, Anderson B, Robertson VJ, and Spielholz NI, Monophasic and biphasic stimulation evoke different responses, *Muscle Nerve*, 28:239-241, 2003.

#### Acknowledgements

This research was supported by a grant (02-PJ3-PG6-EV03-0004) of the Korea Health 21 R&D Project, Ministry of Health & Welfare, Republic of Korea. The experiments performed in this study comply with the current laws of Korea.