THE EFFECTS OF ALTERNATING STIMULATION SEQUENCES ON ISOMETRIC TENSION AND FATIGUE RESISTANCE IN THE DOG GASTROCNEMIUS

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Abstract – In this study we examined the contractile characteristics of the gastrocnemius muscles of six dogs under the isometric condition by applying stimulating pulses to different two motor branches of the tibial nerve. The synchronous and/or the alternating sequences of stimulation were applied to these two motor branches through two pairs of bipolar stainless wire electrodes. In the alternating sequence of supramaximum stimulation at low rates, smooth contraction and higher tension of the gastrocnemius could be obtained and the minimum fusion frequency was lower as compared with the synchronous supramaximum stimulation. In addition, the alternating stimulation sequence could contribute to maintain the isometric tension with higher fatigue resistance, and thus, resulting in shortening the half relaxation time as compared with the synchronous stimulation. These results suggest that the alternating stimulation sequence would be a useful method to realize smooth contraction of the muscles with minimum fatigue.

Keywords: 1交替刺激, 2融合频率, 3等长张力, 4疲劳

1. Introduction

At present, the force of muscle contraction has been controlled by modulating stimulus amplitude, frequency or pulse duration in functional electrical stimulation (FES). However there have not still been any established modulation modalities that realize the contractile characteristics of the normal muscle, such as recruitment and firing rate of motor units. We have controlled muscle contraction by modulating amplitude of pulses fixed at constant frequency and duration. In this method reverse recruitment from larger to smaller motor units is provided, so that sophisticated control of muscle contraction with higher fatigue resistance is not easy to achieve.

It was reported that smooth contraction in a single muscle was obtained by applying low frequency electrical stimulation to different groups of motor units in rotation [1]. However this method was difficult to apply clinically because sacral and lumber nerve roots were detached from the spinal cord for stimulating different groups of motor units. In this study we examined the contractile characteristics of the gastrocnemius muscles of six dogs under the isometric condition by applying synchronous and/or the alternating sequences of stimulation to different two motor branches of the tibial nerve.

2. Methods

A. Dissection and fixation

Six dogs weighing between 10 and 12.5 kg were anaesthetized intravenously with pentobarbital sodium. Both lateral and medial heads of the gastrocnemius and two motor branches supplying them were exposed leaving blood supply and nerve supply through dissecting from the surrounding structures. The biceps tendons were detached from the gastrocnemius tendon and other muscles supplied from the tibial nerve were denervated. After dissection, bipolar Teflon-coated stainless steels wire electrodes with a diameter of 0.075mm (AM system, USA) for stimulation were sutured on the epineurium of the two motor branches microsurgically. These suture sites were covered with nylon tubes respectively and immersed with liquid paraffine. The tips of the electrodes were deinsulated for 1mm and the inter-tip distance was fixed at 1mm.

Two nails were driven into the femur and the tibia, respectively and heads of each nail, which were fixed on apparatus with a force transducer (CPGage-9500, Aikoh engineering, JAPAN) finally, were connected to metal bars externally at 45° flexion of the knee joint. One stitch was put on the tendon as a marker for adjusting muscle length during measurement. The site of this stitch was corresponded to the level of the tibial nail where the ankle joint was in 30° plantarflexion. Then the calcaneus was sawed at 1 cm distal from the attaching portion of the Achilles tendon for detaching the gastrocnemius. Distal end of the Achilles tendon was
split longitudinally and a hook connected to the force transducer was pushed through this split. Muscle length corresponding to 30° planterflexion of the ankle joint was adjusted by a screw which was attached to the calcaneus via a force transducer until the tibial nail and the stitch came into the same level.

B. Electrical stimulation

The medial and lateral heads of the gastrocnemius were fully activated through supramaximal electrical stimulation to muscle branches of the tibial nerve supplying these two heads. Two stimulation modalities were adopted though both branches were stimulated with the same frequency. The phase shift of both pulse trains with the same frequency was 0° and 180° in the synchronous and alternating stimulation modes, respectively. For examining fusion frequency in these two stimulation modes, stimulating pulse trains with frequencies of 5 Hz, 10Hz, 15Hz, 20Hz, 25Hz, and 30Hz were delivered for 2sec. The tetanic stimulation was always carried out with more than 3min intervals.

Furthermore for examining fatigue resistance and recovery capacity in each stimulation mode, sustained stimulation at fusion frequency were delivered for 1min in the four out of six dogs. After the stimulation, the gastrocnemius was stimulated with a single rectangular pulse of 0.1msec duration at 3min intervals for eliciting twitch contraction. These fatigue tests in each stimulation mode were performed with an interval more than 30min. The tension of isometric contraction induced by these two stimulation modes was recorded with a data recorder (RS-800 8-mm data recorder, TEAC, JAPAN).

C. Date analysis

For examining fusion frequency, the recorded isometric tension were digitized at 1kHz sampling rate with a 12bit A/D converter (AD12-16U(98)EH, Contec, JAPAN). The fusion index (F.I.) was obtained as the percentage of a bottom value and a peak value in the oscillating tension curve during stimulation. The comparison of F.I. in these two stimulation modes at each stimulation frequency was made by paired t-test. We also compared the averaged tension in these two stimulation modes at 15Hz that was a minimum fusion frequency in the alternating stimulation mode (F.I.>95%).

For examining fatigue resistance the recorded isometric tension were digitized at 1kHz sampling rate in these two stimulation modes and the values were picked up at 10sec intervals. The values of tension were normalized by the values 1sec after onset of stimulation [2]. For examining recovery capacity the recorded outputs were digitized at 100Hz sampling rate and moving-averaged with 7 points and each half relaxation time was calculated. The half relaxation time was normalized by the values 30sec after the each sustained stimulation mode (% half relaxation time).

2. Results

In the alternating stimulation mode at low rates, smoother contraction of the gastrocnemius could be obtained as compared with the synchronous stimulation mode. Figure 1 shows that stenun during stimulation at 10 pulses/sec through the synchronous and the alternating

![Fig. 1: The tension curve during synchronous and alternating stimulation at 10Hz.](image1.png)

![Fig. 2: The average values of the fusion index of synchronous (dashed line) and alternating stimulation(solid line) (n=6). The fusion index in the alternating stimulation at 5Hz, 10Hz and 15Hz were significantly higher as compared with the synchronous stimulation.](image2.png)
stimulation modes. The F.I. through the alternating stimulation mode at 5Hz, 10Hz and 15Hz were significantly higher as compared with the synchronous stimulation mode (P<0.05). There was no significant difference among the F.I. through the alternating stimulation and the synchronous stimulation modes at 20, 25 and 30 Hz (Figure 2). In addition, figure 3 shows tension during stimulation at 15 pulses/sec through the synchronous and alternating stimulation modes. The alternating stimulation mode gave fused tetanus while synchronous stimulation mode gave unfused one. The average values of tension during stimulation were 15.27 ± 9.9Kg and 20.5 ± 13Kg in synchronous and alternating stimulation modes, respectively. The value of tension through the alternating stimulation was significantly larger than that in the synchronous stimulation (P<0.05)(Figure 4).

The alternating stimulation mode could contribute to maintain the isometric tension with higher fatigue resistance. The normalized isometric tension in the alternating stimulation mode for 1 min increased from the initial values for 50sec after starting of stimulation and finally the tension decreased only 4 % of initial values. With respect to the synchronous stimulation mode finally
3. Discussion

In muscle contraction by FES, there have not still been any established modulation modalities of electrical stimulation that realize the contractile characteristics of the normal muscle, such as recruitment and firing rate of motor units. As a result, sophisticated control of muscle contraction with higher fatigue resistance is not easy to achieve. Therefore it is necessary to established new useful stimulation methods which can be applied clinically. We examined the contractile characteristics of the gastrocnemius muscles of the dogs to confirm whether an alternating stimulation modality applied to different motor branches of the tibial nerve supplying to this muscle was feasible clinically or not.

It was reported that rotational stimulation to different subdivisions of the ventral nerve supplying to the soleus muscle resulted in a smoother contraction and higher tension with lower stimulation frequency [1]. Although electrical stimulation was applied to only two branches to medial and lateral heads of the gastrocnemius, we also observed that alternating stimulation mode caused a reduction of stimulation frequency to each of electrode pairs for fused tetanic contraction with higher tension as compared with the synchronous stimulation mode. However it has been reported that an increase in muscle length increased twitch duration, and thus resulting in the changes of fusion frequency and muscle tension [1]. Therefore it will be necessary to study the interrelation of the length, fusion frequency and tension of the muscle for application of synchronous stimulation mode to different motor branches in FES.

Several studies indicated that slowed relaxation as a consequence of fatigue increased twitch summation and potentiated tension during lower-frequency tetanus [3] [4] [5]. They mentioned that one of the possible explanations to the potentiation of tension is an increase in the myofibrillar calcium sensitivity because calcium release into the sarcoplasm is reduced despite the increased force [6]. Also an increase in relaxation time is attributed to an increase calcium sensitivity that depends on perfusate CO_2 [7]. Our study showed that the sustained alternating stimulation applied to both heads of the gastrocnemius at lower stimulus frequency could contribute to an initial increase in the isometric tension as compared with the sustained synchronous stimulation. The same mechanism mentioned above may explain the phenomena which we observed.

Each % half relaxation time of a twitch tension after the sustained alternating stimulation was always smaller than that in the synchronous. It means that the recovery capacity in alternating stimulation was larger as compared with synchronous stimulation.

These results suggests that the alternating stimulation applied to different muscle branches supplying to a single muscle would be a useful method to realize smooth contraction of the muscles with minimum fatigue.

References
