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SYNTHETIC PROPRIOCEPTIVE FEEDBACK OF RECRUITMENT FORCES IN THE ELECTRICALLY STIMULATED MUSCLE

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ABSTRACT

The open loop Transient Response of Recruitment Forces of Electrically Stimulated Muscle was shown to have 18% undershoot and some 15 seconds settling time. An analytical approach is presented utilizing a synthetic proprioceptive force feedback to completly suppress the transient undershoot. In the approach a mathematical model of the muscle recruitment response was used in conjuction with a simple gain feedback (K). Recruitment was accomplished with high frequency stimulation of the nerve distal to a rate stimulus electrode. The closed loop transient response, upon adjustment of the feedback gain, can provide overdamped, underdamped or critically damped force profile. Critically damped force profile provides satisfactory response for functional performance in addition to inherent force regulation during variable loading/gravity conditions during movement as well as compensation for fatigue.

INTRODUCTION

Stable regulation of muscle force in the intact neuromuscular system is accomplished by complex interaction of action-potential firing rate, recruitment of motor units according to their size, and proprioceptive feedback (1-6).

During direct electrical stimulation, only action-potential firing rate could be properly controlled, whereas reverse recruitment occurs if stimulus pulse amplitude is manipulated. Furthermore, proprioceptive feedback regulation of muscle force is not available (6). The rapid onset of fatigue is another factor resulting from high firing rates, reverse recruitment, and lack of proprioceptive feedback.

Undesirable force characteristics were circumvented by a recruitment control scheme in which high-frequency stimulation was applied distally on the muscle nerve-to-rate stimulus electrodes. The high-frequency stimulus induces neuromuscular blockade, and on manipulation of its pulse amplitude the blockade is gradually removed, with the small motor units becoming active first, such as in normal recruitment (7). High-frequency stimulation has been applied as means for improved muscle force profile and fatigue behavior (8), and frequency and time response studies have also been reported (9,10).

Time-response characteristics indicated a nearly instantaneous rise time, 18% peak undershoot at 4 seconds, and 15 seconds settling time. A synthetic proprioceptive feedback is considered, for further improving the force profile, primarily in terms of transient response and force regulation under variable load/gravity conditions, and for minimizing the effect of fatigue. In this paper, one such proprioceptive feedback system is analytically derived for improved regulation and transient response behavior of the muscle force profile.

METHODS

In early studies on a limited number of cats, the model of the soleus muscle and stimulator during high-frequency induced recruitment was obtained for the open-loop portion of the system shown in Figure 1.

The model consisted of two double poles and a remote zero (9). Further studies improved the accuracy of the data and the resulting model consisted of a triple pole, a single pole, and gain as shown below.

$$SM(s) = \frac{K}{(s+a)^3 (s+b)}$$

Where

S (s) - model of the high frequency stimulator

M (s) - model of the muscle during recruitment

a, b - the time constants.

Force profiles of the muscle were taken during (1) direct stimulation; (2) high-frequency stimulation; (3) high-frequency stimulation imposed 2-3 seconds after direct stimulation; and (4) sinusoidal variation of high frequency superimposed 2-3 seconds after onset of direct stimulation. Figure 2 shows the force profile of the four recordings.

To verify and compare the model obtained by frequency response techniques with the time-response profile of the muscle, we obtained the response to step input of high-frequency recruitment stimulus as follows:

$I(s) = 1/s$ - step input of high frequency recruitment stimulus.

$$F(s) = I(s) \cdot SM(s)$$

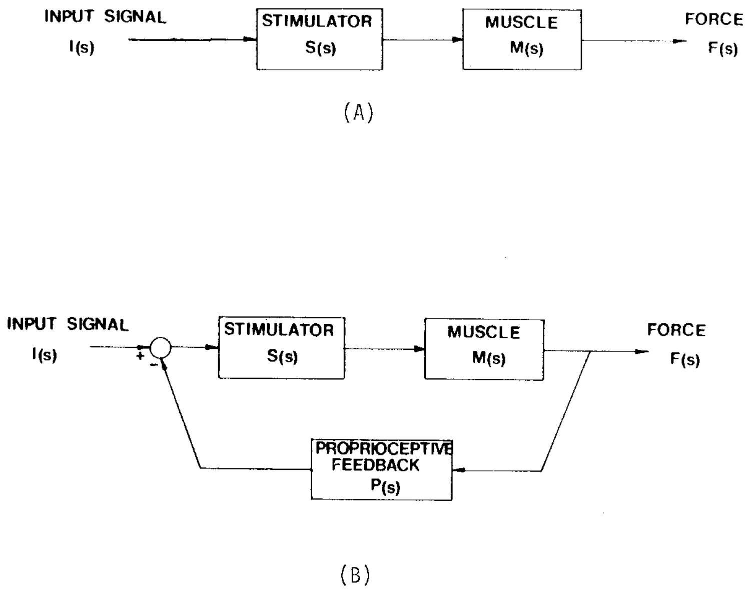

FIGURE 1

Schematic of the (A) Open loop system, and (B) Closed loop system incorporating the synthetic proprioceptive feedback.

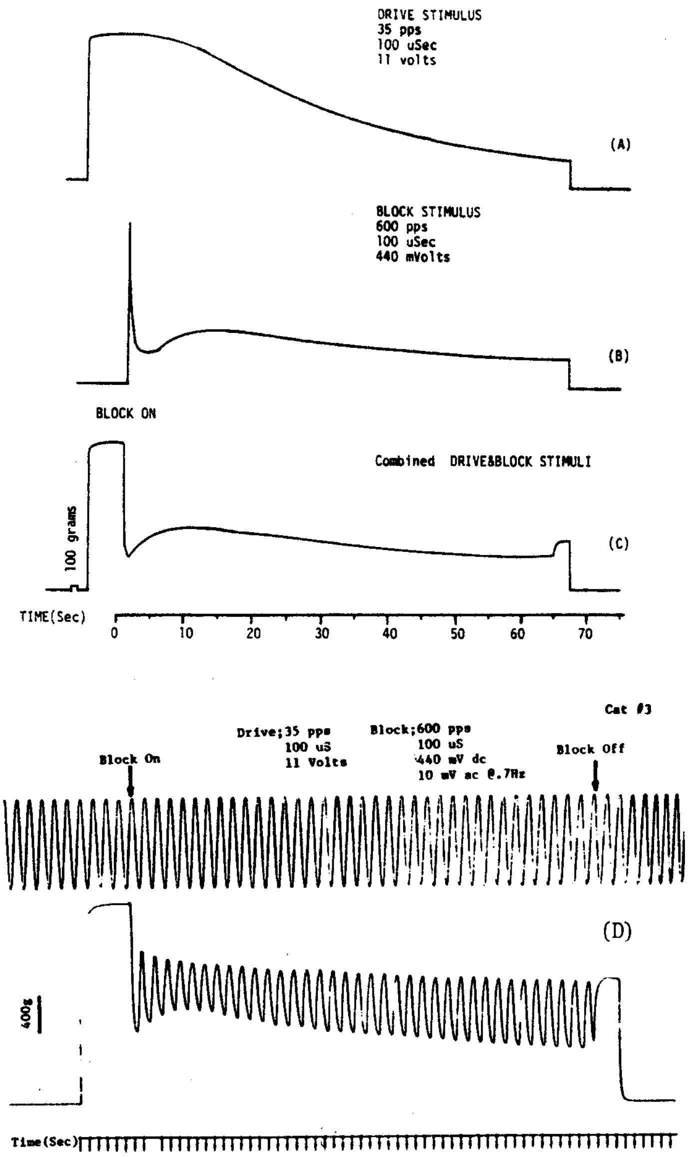

FIGURE 2
Time response to (A) Direct stimulation,(B) High frequency stimulation (C) High frequency stimulation superimposed on direct stimulation,and (D) Sinusoidal high frequency stimulation superimposed on direct stimulation.

and the time response is

$$f(t) = L^{-1}\left[\frac{1}{s} \cdot \frac{K}{(s+a)^3 (s+b)}\right]$$

or $f(t) = A - \frac{B}{2} t^2 e^{-at} + Ce^{-bt}$

Figure 3 graphically represents the individual force components as well as their summation. The transient response obtained analytically (Fig. 3b) compared with its experimental counterpart (Fig. 2b) indicates satisfactory performance of the model.

Although the model is satisfactory compared with the experimental response to step input, it is not under the same conditions for application in dynamic muscle control because the background rate stimulus is absent. The absence of initial spike (Fig. 2b) is evident in Figure 2c, showing the force profile for both rate and recruitment stimulus. Since the muscle was already in an active contraction, the arrival of additional action potentials at high frequency immediately contributes toward ACH or Ca^+ depletion at the endplates or the reticulum respectively, without having to activate them first as in Figure 2b. The remainder of the force response of Figure 2c takes on the exact pattern as in Figure 2b, including the temporary loss in block (or force increase) peaked at 4 seconds and the subsequent long settling time to the steady state level.

Figure 4 gives replotting traces c and d of Figure 2 as percent blocking effectiveness and percent peak-to-peak force vs time. In both cases, the effect of high-frequency block is diminished by the 4th second, probably due to partial recovery of ACH or Ca^+ depletion (11), but the physiology is unable to keep up with such high rates, which eventually settles down in a partial blockade.

From the engineering standpoint it is advantageous to reduce the undershoot as well as the settling time for improved performance of the muscle. An appropriate force feedback element could be considered for such purposes with the additional advantages of force regulation during variable loading/gravity conditions as well

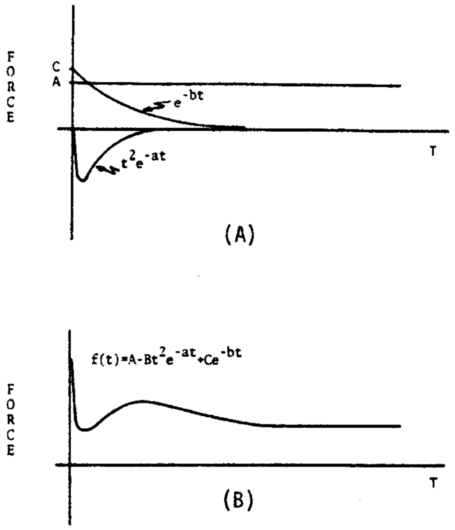

FIGURE 3
The analytical transient response of the open loop system showing the (A) Components of the response, and (B) Integrated response.

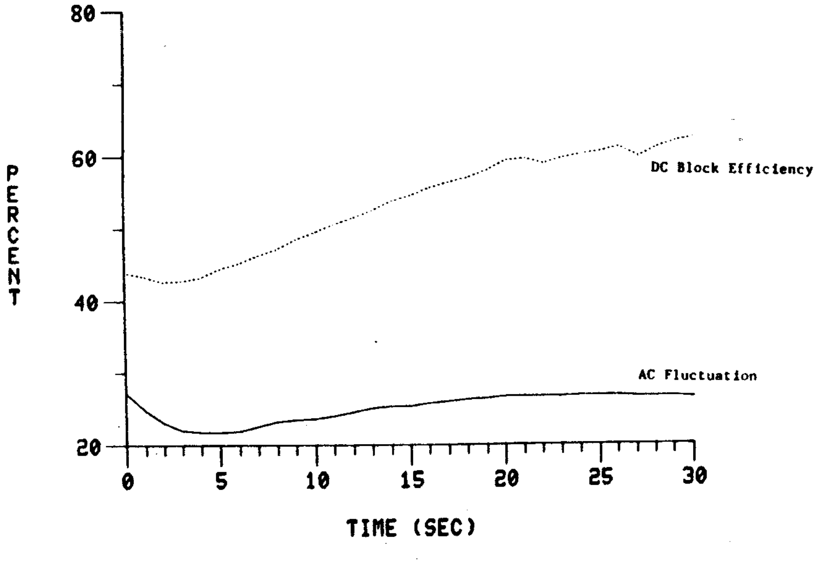

FIGURE 4
The transient response of the open loop system to step input(DC),and to sinusoidal input superimposed on step input(DC).

as during fatigue. Such a closed loop system is shown in Figure 1. For force regulation a simple gain in the feedback may suffice to also improve the transient response.

Consider again a step input in high-frequency recruitment stimulus with

$I(s) = 1/s$

and $P(s) = k$

then

$$F(s) = I(s). \frac{SM(s)}{1+SMP(s)}$$

and

$$f(t) = L^{-1}\left[\frac{1}{s} \cdot \frac{K}{(s+a)^3(s+b)+kK}\right]$$

for which the estimated time response then is

$$f(t) \cong A'-B't^2e^{-at} + \frac{C'}{k}e^{-bkt}$$

The net effect of the feedback is therefore expressed as control over the amplitude and decay time of the third component. Indeed, with proper adjustment of the feedback gain it could eliminate the undershoot observed in the open-loop time response as shown in Figure 5c.

A simple feedback gain, when properly adjusted, may substantially improve the transient response as well as provide inherent force regulation during loaded movement and fatigue.

Although the transient response is substantially improved by the feedback, the stability of the system should be tested for possible unstable operation at certain gain (k) values.

Ideally, proprioception also includes muscle length feedback, which was not addressed here. This could be provided in a similar manner as a secondary feedback loop, although its benefit to the the system performance is questionable, primarily due to the difficulty in implementing an in vivo physical sensor to measure

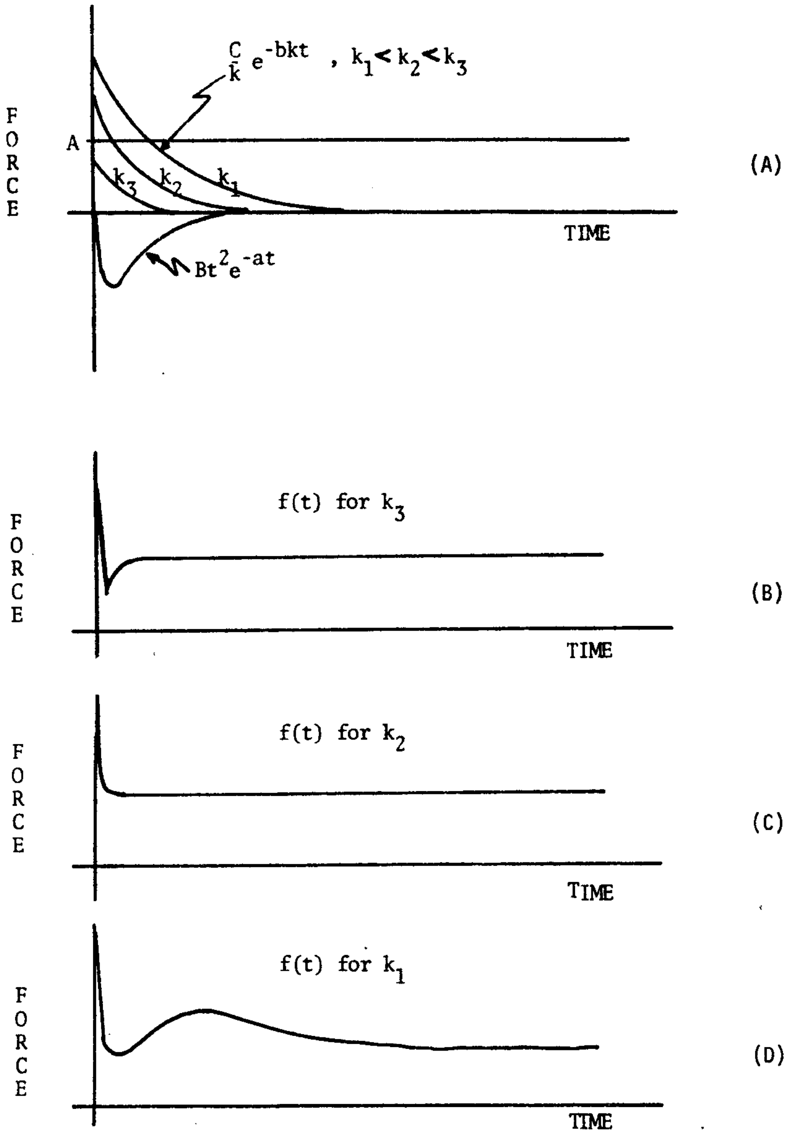

FIGURE 5

The transient response of the closed loop system to a step input of high frequency stimulus,(A)The various components of the resonse,(B) (C) and (D) the response of gradually increasing feedback gain.

muscle length. Force measurements could be relatively simple by implanting a solid state sensor near the tendon of the muscle in an implantable neurostimulation system.

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