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DYNAMIC MODEL OF NORMAL AND DENERVATED MUSCLFS IN MAN

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ABSTRACT

The joint moment in ankle was measured in isometric condition as a response to electrical stimulation. A dynamic biomechanical model has been synthesized for both innervated and denervated tibial anterior muscles.

INTRODUCTION

Dynamic response of muscles contraction due to electrical stimulation has been primar ly studied for model synthesis (Morecki et al., 1964, Vodovnik, 1964, Crochetiere et al., 1967, Trnkoczy et al., 1976, Reberšek et al., 1982). In recent years much information has been gained as to the processes involved in excitation - contraction coupling of sceletal muscles (Wallinga de Jounge et al., 1981). The biomechanical model enables to study the differences of dynamic responses of normal innervated and complete denervated muscles. Functional electrical stimulation methods of complete denervated muscle tibialis anterior has been proposed in 1981 (Vodovnik et al., 1981, Valenčič et al., 1982,1983, Eichorn, 1983). It has been shown that only a narrow range of parameters of electrical stimuli is adequate for stimulation of such muscles. These parameters were markedly different in comparison to the parameters suitable for stimulation of innervated muscles through the nerve trunk. The mechanism of direct denervated muscle stimulation has been examined by means of biomechanical modelling of ankle joint.

Recent work (Nix, 1983) has shown that isometric stimulation of denervated rabbit's muscle decreases the rate of atrophy and denervation induced changes in contractile behaviour.

Eberstein et al., 1981 compared the diameters muscle fibers in stimulated and nonstimulated denervated rats. Their findings demonstrated that stimulation significantly retarded the atrophy of both Type I and Type II fibers.

METHODOLOGY

Measurements of ankle joint responses were performed in four male and one female healthy subjects of age 24 to 50 years, and a 20 years old female patient with complete denervated muscle tibialis anterior. The subject was four months after onset of peripheral lesion of peroneal nerve trunk.

These subjects have been stimulated with rectangular monophasic stimuli which were obtained with current source stimulator. Durations of the stimuli were in range from 1 ms to 1000 ms. The amplitudes were adjusted to a level which elicited a single twitch response. Amplitudes of moment were less than 0.5 Nm. Such a low level of moment was used in order to reduce nonlinearity of the neuromuscular and biomechanical ankle joint system.

The stimulation was applied through surface bipolar spunge electrodes 16 cm^2 of size with 1 % saline water solution. The electrodes were positioned over pretibial muscle group. Distance between the electrodes was approximately 20 cm. Detailed positioning of the electrodes was performed according to the maximal response. Anode plus pole was in all experiments positioned proximally.

The measurements of moment were done with three dimensional cordinate brace in isometric condition. Trace of moment as a function of time has been recorded with a Brush recorder.

The selection of patient has been done according to standard clinical and neurological examinations: General muscle test, nerves conduction velocity determinations, strength duration curve recording and needle electromyographic recording of pretibial muscle group. In addition, the stimulation with typical tetanic stimuli-pulse duration 0.1 ms and frequency 40 Hz - was applied to test if some innervated muscle fibers are still present inside the pretibial muscle group. In all particular subjects which have been examined, no measurable responses were obtained.

In the contrary, in three subjects some very low subclinical electromyographic activity has been found, but with other tests it has been shown that nerves and muscles were clinically without any activity. The volitional movements of the ankle as well as response on tetanic stimulation, mentioned above has been not detected. For the purpose of this investigation, these cases have been classified as partially denervated. These patients were treated with identical methodology as patients with complete denervation of pretibial muscle group.

This report describes the difference between dynamic response of normals and patients with complete denervated flexors of ankle joint due to peripheral lesion of peroneal nerve. The antagonistic muscles group were innervated. This fact induced some difficulties into the model parameters identification procedure. Modelling of neuromuscular and biomechanical system of ankle joint with parameters identification method has been realized. The well established approach by Trnkoczy et al., 1976, has been used. However, in our approach Trnkoczy's model was simplified to a second order dynamic linear system. A delay of response is taken into account and fitted directly into the solution of the biomechanical expression (eq.1).

$$J\ddot{\varphi} + B\dot{\varphi} + k\varphi = T_{iso} \qquad (1)$$

where B is viscosius damping of contracting and relaxing muscle group, J is rotary moment of inertia of foot about the ankle axis, and k is spring constant from ago-and antagonist. T_{iso} is the inner generator moment of contracting muscle. General solution of the equation (1) is in form (2). The isometric ankle moment is considered as an output variable. The input variable is supossed as an unit impulse function and is proportional with the inner moment generator. This radical simplification is possible because of low range of the moment elicited by stimulation.

$$\varphi = \frac{a_3}{a_1 - a_2} \left(e^{a_1 t} - e^{a_2 t} \right) \tag{2}$$

This solution was not fitted satisfactory with data which have been measured on subjects. For correction of error a delay τ has been included into the solution of eq. (2). The following solution has been proposed:

$$\varphi(t, \tau) = \frac{a_3}{a_1 - a_2} \left(e^{a_1 (t-\tau)} - e^{a_2 (t-\tau)} \right) \tag{3}$$

Eq.3 is valid for $t \geqslant \tau$.

The preceding method has been concerned with the formulation of mathematical model of biomechanical dynamic system on the basis of a priory theoretical and experimental data. The process of identification consists of the experimental determination of the model and the process of validation consists of verifying experimentally whether a particular model or a general type of model postulated for the system of ankle joint under electrical stimulation represents an adequate description.

The identifiaction process has been based on modified Monte Carlo process, simulated on personal computer (Spain, 1982, Finkelstein et al., 1978).

The first evaluation of records has been done with aids of parameters t_1, t_2 and t_3. The meanings of these parameters are illustrated in Fig. 1; t_1 is delay of the response after the first front of stimuli pulse; t_2 is time till maximum and t_3 is the complete duration of the dynamic response. The readings of these parameters are collected in Table I for normal and in Table II for pathological subjects.

Pulse width ms	t_1 ms	t_2 ms	t_3 ms	
10	17	93	350	Normal patterns
30	20	93	350	
50	20	93	350	
100	20	93	370	
500	20	100	400	
1000	17	100	400	

TABLE I

Pulse width ms	t_1 ms	t_2 ms	t_3 ms	
10	240	480	700	Denervated patterns
30	160	420	640	
50	200	360	720	
100	120	320	800	
500	120	280	820	
1000	120	280	900	

TABLE II

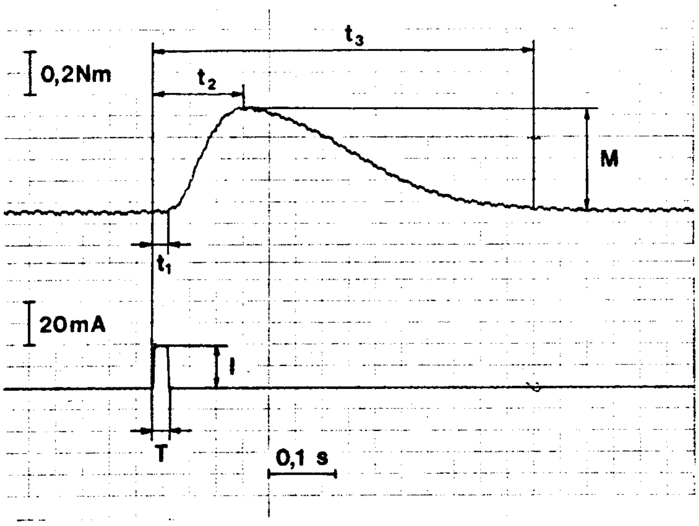
t3
0,2Nm
t2
M
t1
20mA
I
T
0,1 s

Fig. 1.

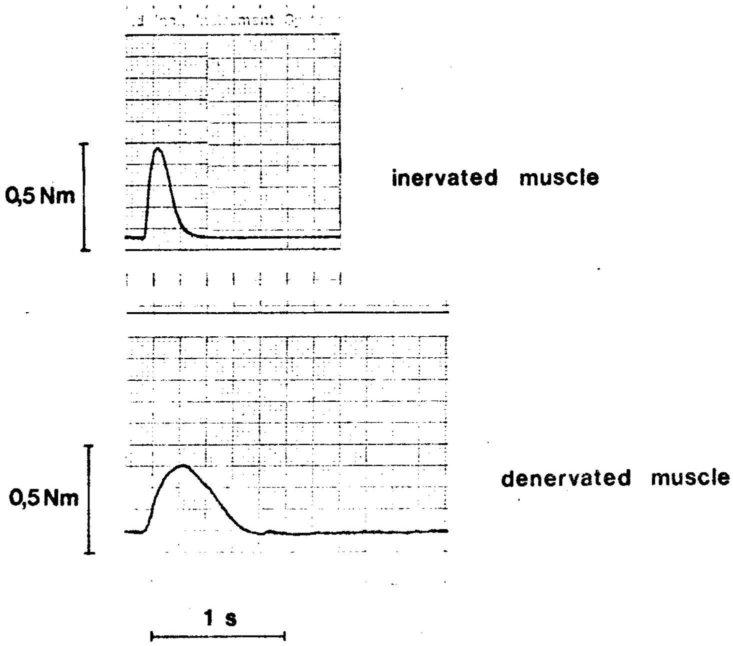
0,5 Nm
inervated muscle
0,5 Nm
denervated muscle
1 s

Fig. 2.

Comparison of data in Tables I and II show that the delays, maximal occurences and durations of responses are significantly greater in pathological case than in normals.

We assume that there are two main reasons for results shown in Tables I and II. First, the activation of antagonistic pair of muscles since plantar flexors of ankle joint are innervated in this particular case. The response on single twitch stimulation is delayed approximately 20 ms and maximal occurance is at 100 ms in normals. Only after this time activation of direct stimulated agonistic pair of muscle can elicit moment in direction of dorsal flexion. By shortening of pulses greater delays were obtained. Second, the generation of force in denervated muscle is not a step function as we assumed at the beginning and proposed a linear model of ankle joint neuromuscular system. The difference occured due to changes in excitation-contraction coupling of denervated sceletal muscles. The quantiative difference of dynamic responses of innervated and denervated muscles is shown in Fig. 2.

The play of denervated agonistic and innervated antagonistic muscles dependent on pulse durations are shown in Fig.3. Stimulation current has been fixed to 20 mA. Biomechanical modelling of described system involved supplementary difficulties. In additional measurement of responses the stimulation current has been adjusted to a level which does not elicit the moment in plantar flexion direction. This record has been the basis for essential modelling and parameters identification procedure of data which were experimentally obtained.

Fig. 4 shows experimental data of normals denoted by circles and fitted mathematical model denoted by dots. The model has been based on Eq. 1 to 3. The parameters in the proposed model are $a1 = -11.9$ (1/s), $a2 = -12.1$ (1/s) and $a3 = 5.7$ (Nm/s) and $\tau = 0.015$ (s).

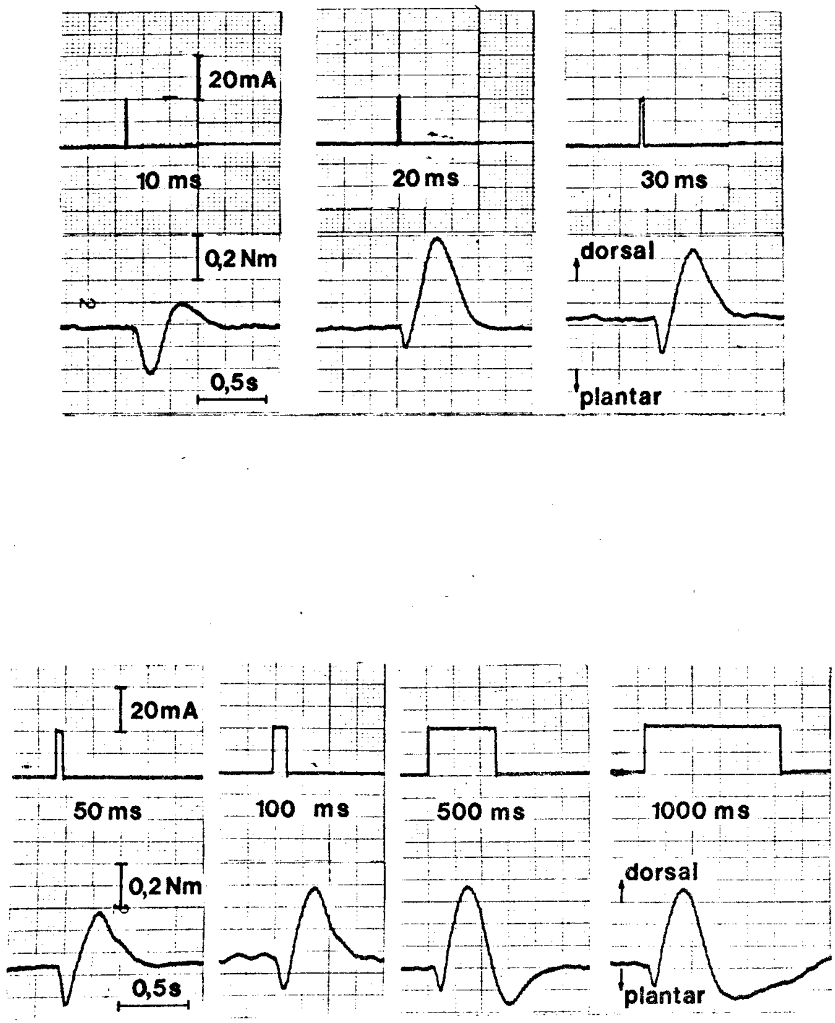
20mA
10 ms
20 ms
30 ms
0,2 Nm
dorsal
plantar
0,5s
20mA
50 ms
100 ms
500 ms
1000 ms
0,2 Nm
dorsal
plantar
0,5s

Fig. 3.

Fig.5 shows record of experimental data of denervated subject denoted by circles and appropriate fitted mathematical model denoted by dots. The parameters of proposed model are a1=-4.9 (1/s), a2= -7,3 (1/s), a3=6,3 (Nm/s) and τ = 0.1 (s).

The results showed marked differences in dynamic responses on single pulses of stimulation currents. Currents were fixed on 10 mA and pulse width was 100 ms. The best fitting was obtained according to minimum square error criterion.

Velocity constants a1 and a2 are significantly greater in the normal than in pathological pattern, but the delay of the response is distinctly longer in pathological than in normal pattern. The parameters estimated with second order dynamical model are in agreement with the models in references (Trnkoczy et al., 1976, Reberšek et al., 1981).

CONCLUSIONS

The Mathematical model of biomechanical dynamic system of denervated agonist muscles of the ankle joint has been examined and evaluated. The complexity of such a system has been demonstrated.

The distinction of denervated skeletomuscular dynamic system has been analysed but it is dificult to conclude that the basic reasons of the differences are only changes of the biomechanical properties of ankle joint and muscles belonging to this joint. It is possible that such a significant difference originates due to alternations in the force generator of the denervated muscle fibers within the excitation - contraction coupling process.

These conclusions might be useful as a diagnostic criterion for the biomechanical estimation of neuromuscular system affected due to peripheral nerve lesion.

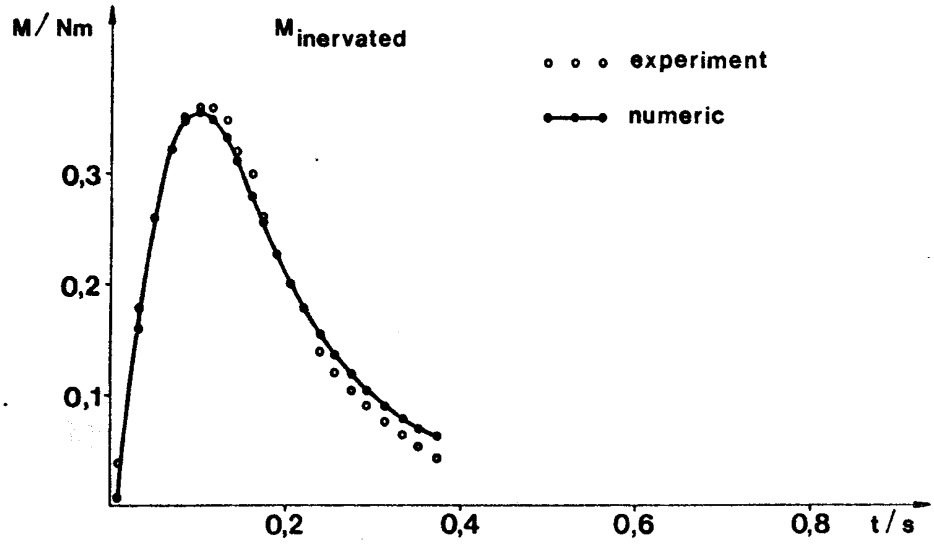
M/ Nm
Minervated
o o o experiment
numeric
0,3
0,2
0,1
0,2
0,4
0,6
0,8
t/s

Fig. 4.

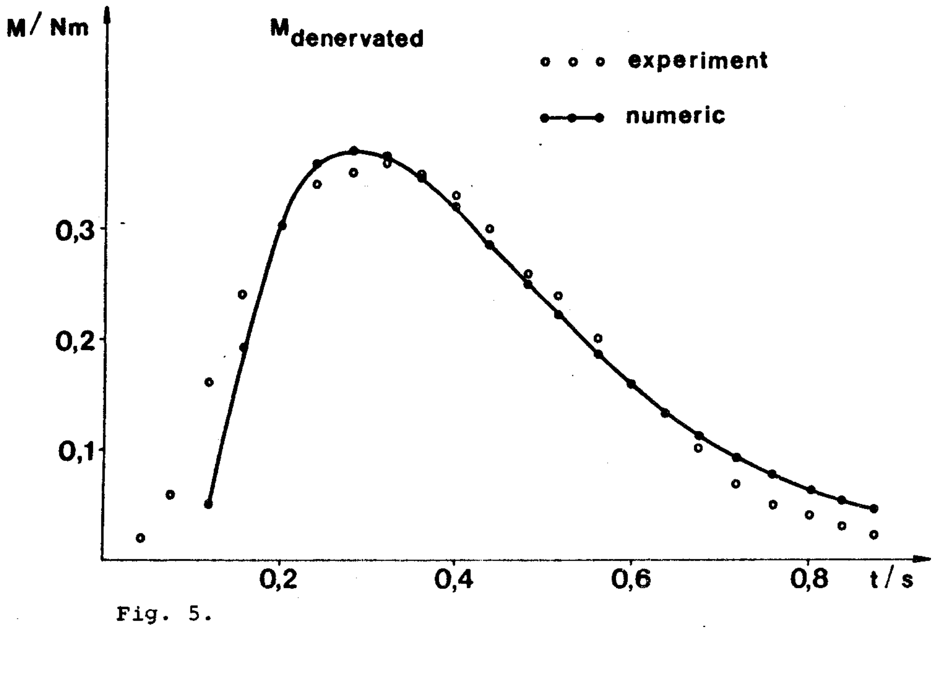
M/ Nm
Mdenervated
o o o experiment
numeric
0,3
0,2
0,1
0,2
0,4
0,6
0,8
t/s

Fig. 5.

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