ELECTRICAL STUDY OF MUSCULAR RESPONSE UNDER ELECTRICAL NERVOUS STIMULATION

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Summary

Functional - electrical - stimulation (FES) may be a realistic approach to the problem of functional rehabilitation of the physically handicapped. Muscle contraction (triceps and anterior tibialis of dogs) is analysed in both the isometric and anisometric modes, with measurements taken by special force and angle transducers. A special mechanical device associated with the angle transducer corrects parasitic rotations. The force developed by the muscle is measured as a function of three parameters of the stimulation rectangular pulse train which are amplitude, pulse width and frequency. The width of the pulses in the train is chosen as the best command variable. Finally, an experimental procedure for a dynamic study is proposed.

I - Introduction

Analysis of locomotion and prehension processes have shown that it is possible to model a human body as an articulated system with a large number of degrees of freedom (1), (2). It is necessary to obtain a mathematical model of the process to control the motion of all the stimulated joints (3).

A bibliographic investigation on this problem (4) shows that the single component -the joint- of such a complex system has not been very well characterized. We have designed specific experimental devices to be used on dogs' ankles. With these transducers, it has been possible to analyse the muscular contraction properties and to define the form of the stimulating signal (5), (6), (7). The neuro-muscular system and the joint can then be represented by an input-output system including stimulator. The motion equation shows up biomechanical parameters. Finally, an experimental procedure to define an automatic control is proposed (8), (9).

II - Experimental devices

Figure 1 shows the neuro-muscular system and joint:

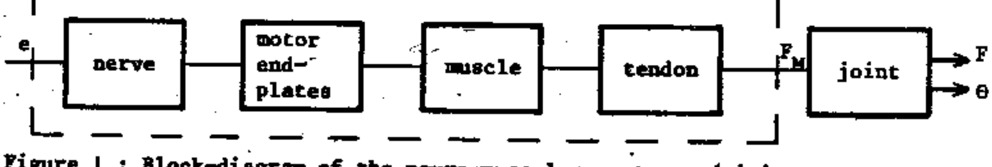


Figure 1 : Block-diagram of the neuro-muscular system and joint

The motor-end plates and the tendon respectively are the interfaces between the muscle and the nerve at the beginning of the loop and the joint at the end of the loop. The nerve drives the input signal of the process, the joint is the controlled part of the system. The parameters which can be easily picked up are the input signal (e) transmitted along the nerve and the angle of rotation of the limb (θ) or the force (F) transmitted by the joint (figure 2).

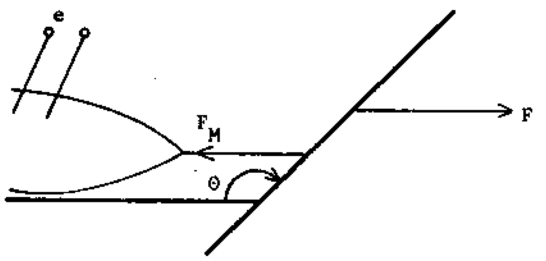


Figure 2

The force F_M developed by the muscle may also be measured by tendinous transducers. The difficulties lie in the testing and mainly the method of attaching these transducers which must not irreversibly damage the tendon. Only qualitative results have been obtained by this method (4).

The force developed by the limb is directly measured with a dynanometer ring on which are attached four bridge-connected metallic strain-gauges (figure 3). A strech on the ring generates a resistive linear variation of the gauges. The transducer size has been defined to obtain a sufficient sensibility (1,6 mV/N) with a supply of 4V (necessary to limit the power).

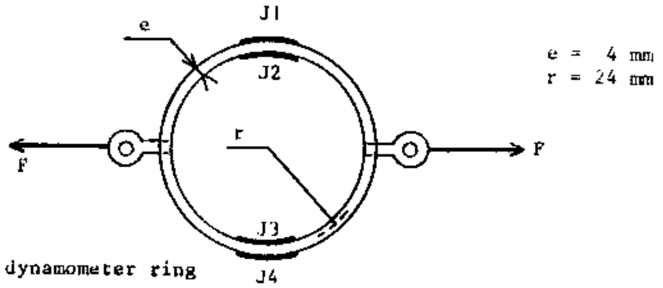


Figure 3 : The dynamometer ring

The angle of rotation of the limb is measured by a potentiometric system with negligible friction, which gives the joint angle indepeadant of the position of its apex and the plane of rotation (figure 4).

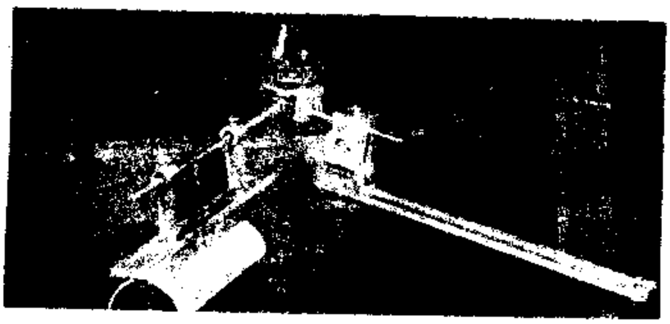
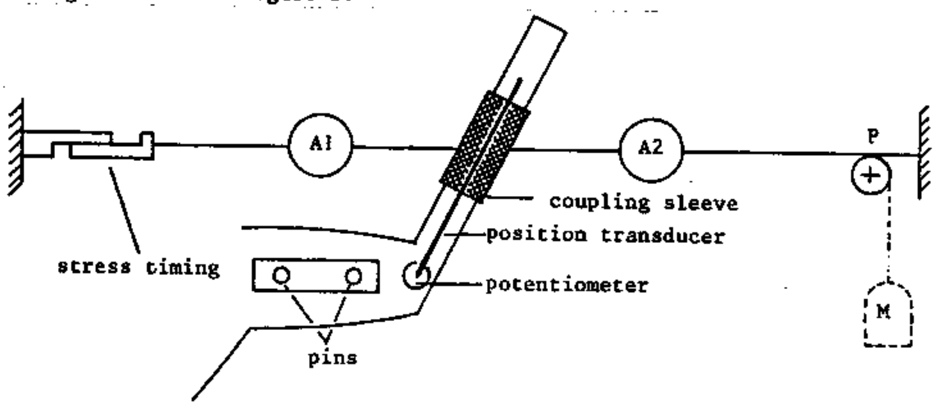


Figure 4 : The position transducer

It allows the measurement of one rotation independant of the parasitic mechanical displacements (if these are small). The ankle can then be compared to a system with a single degree of freedom. This device includes one part (on the right) mastered to the tibia by two pins and another (on the left) that follows the motions of the foot by means of a coupling sleeve. Mechanical adjustements are necessary so that the main axis of rotation of the joint and that of the potentiometer are the same. In this way, the torque friction is reduced to a minimum. Measurements are performed with a potentiometer with a moulded plastic track MCB-H33. Its nominal resistance is 1 kΩ ± 10 % and the linearity is better than 1 %.

The pins, that are used to master the position transducer are also designed to maintain the tibia in a stable and horizontal position : they are secured in an external metallic frame which is fastened to the operating table. If isometric measurements are taken (θ constant), the dynanometer ring only is used. In the anisometric mode, the potentiometric transducer picks up the displacements of the free lever, loaded externally by a weight M. The experimental setting is shown in figure 5.



Fitting of the dynanometer rings A_1 and A_2 in the isometric mode. Steel wire-cables enable their insertion between the foot and the metallic frame. In the anisometric mode, the rings are left out. The foot is loaded by an external weight M applied on the centre of gravity by way of a guide pulley P (in dotted lines).

Figure 5 : Experimental procedure.

III - Search for control variables

The contraction of muscle comes from energy variations transmitted along the nerve and the motor end-plates. We have therefore used firstly a stimulator which delivers rectangular pulses whose amplitude, width and frequency can be regulated independently. The signal is sent along the nerve by electrodes (internal of external popliteal sciatic, according to whether muscular contraction of the agonistic or antagonistic group is needed).

III - 1 The electrodes

They are made of carbon fibers ; the advantage of this material is that it is impolarizable and well tolerated by the human body (figure 6).

By coupling several carbon fibers in a flexible braid, it is possible to decrease the impedance of the electrodes (< 10Ω). The carbon braid is then attached to an artificial tissue (Rhodergon). The support is large enough to surround the nerve without compressing it.

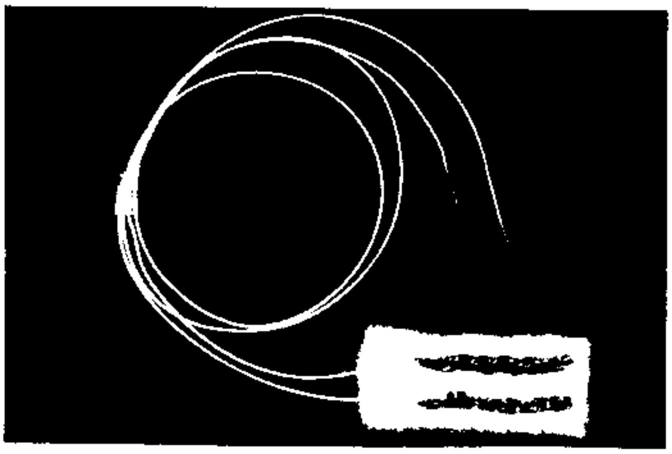


Figure 6 : The electrodes.

III - 2 Influence of the different stimulating parameters on the muscular contraction (4)

A succession of experiments in the isometric mode allowed us to verify that, between 25 Hz and 60 Hz, the force developed by the muscle depends only on the width and the amplitude of the pulses. It indicates therefore that the force cannot be controlled in a useful way by variation of the stimulating frequency.

On this range of frequency, the force can be drawn with a fixed pulse parameter (width or amplitude) when the other is moving, as shown in figure 7 and 8. When the pulse width (or amplitude) rises, the developed force quickly increases from threshold and reaches saturation. It stands out that the maximum force is obtained for an amplitude (or width) which is as an inverse function of the pulse width (or amplitude).

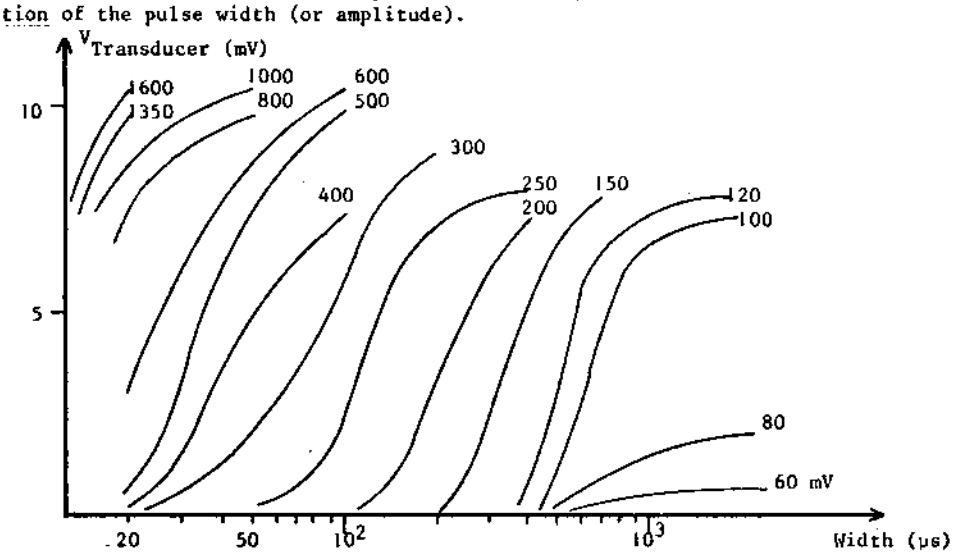


Figure 7 : Force developed by the tibial as a function of the width of the stimulating impulses, for fixed amplitudes.

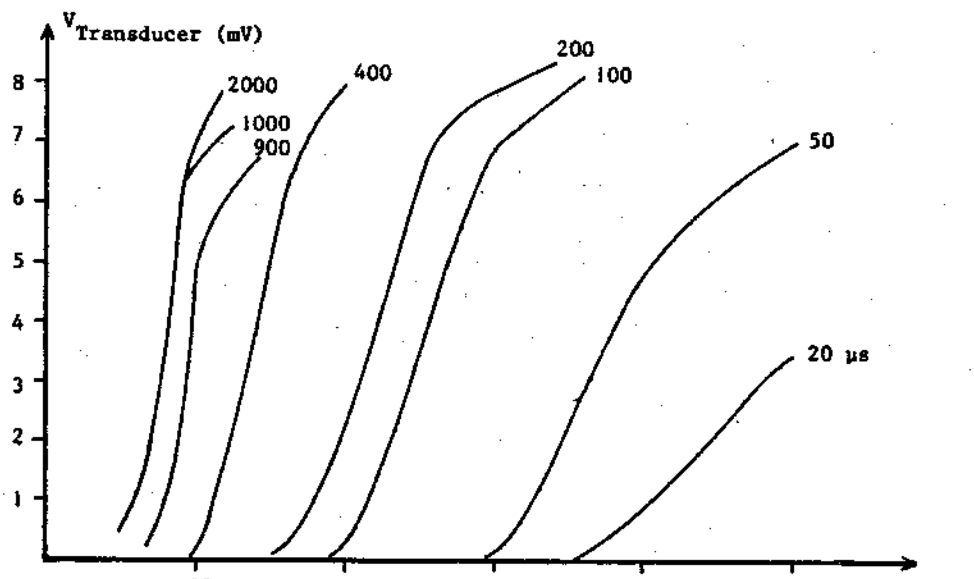


Figure 8 : Force developed by the tibial in relation to stimulating amplitude for fixed widths.

The pulse width variation effect can be compared with that of a pulse amplitude variation. The choice of either parameter as a control variable depends on a criterion which is a function of the result required. If, for instance, we want to implant a stimulator near the nerve, we would be led to consider an energetic criterion and would choose a pulse width variation. This allows one to obtain the maximum developed force by the muscle with a minimum power consumption. On the other hand, if a short response time is needed between the application of the stimulating signal and the appearance of the maximum force, it would be better to control by a pulse amplitude variation. These criterions are not compatible eabh other but, for practical application , it is easier to control the variation of only one parameter. We then chose a pulse width modulation and fixed the amplitude at a correct value to get a short enough response time. In this way, it is also possible to minimize the pain coming from the artificial stimulation , as was established by Trnkoczy and Gračanin (6).

We then designed a stimulator which delivers width-modulated pulses. This realizes a conversion of the input modulation voltage (V_{MOD}) produced by an external generator into pulse width. Between 100 µs and 400 µs, and with a pulse amplitude between 100 mV and 150 mV -a range wide enough for our needs- the conversion is a linear function.

IV - Expérimental procedure

With a view to chronically implanting a stimulator near the nerve, we have been led to consider the following input-output system shown in the block-diagram of figure 9.

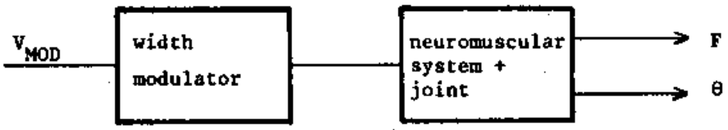


Figure 9 : Block-diagram of the input-output system

This means that the modulator is included in the loop, so we have to establish a relationship between the modulation voltage V_{MOD} and the position θ or the force F transmitted to the free lever.

The neuro-muscular unit transforms an electrical stimulus into a mechanical effect F_M on the tendon. This first relationship V_{MOD} - F_M is of an electro-mechanical type. The second, F_M - θ is mechanical only and takes into account the external torques applied to the foot. In order to be realistic, we have to introduce a viscous damping ξ as a property of the joint and consider that, if the agonistic group only is stimulated, the antagonistic one puts up a passive resistance (F_{ANT}) to the motion.

The evaluation of biomechanical parameters and variables of the joint, as they appear in the anisometric mode, is performed figure 10.

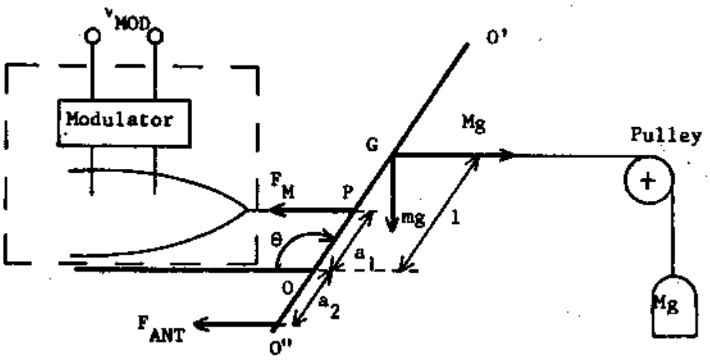


Figure 10 : Evaluation of biomechanical parameters

If we assume that the agonistic group only is stimulated, we can write the following equation of motion :

$$J \ddot{\theta} = \left(a_1 F_M - a_2 F_{ANT} - Mgl\right) \sin \theta + mgl \cos \theta - \xi \dot{\theta} \qquad (1)$$

The term J represents the moment of inertia of the free lever OO' in relation to the axis O of the joint and m is the mass of the foot and the position transducer together.

To solve this equation, three kinds of experiments must be performed.

IV - 1 Experiments in the anisometric mode

The simplified diagram is shown in figure 10. The position transducer allows the measurement of θ as a function of the modulation voltage V_{MOD} used and the external load M transmitted to the centre of gravity G of the free lever.

IV - 2 Measurements of the passive effects (F_{ANT}) of the joint

We need to evaluate the passive resistance of the non-stimulated muscular group and the torque introduced by the stiffness of the ligaments and the mechanical limits of the joint. We manually twisted the foot from one limit to the other. If we couple the position transducer to the dynanometer ring loaded by a known weight M (figure 11), it is possible to record the passive forces F'_{ANT} as a function of θ.

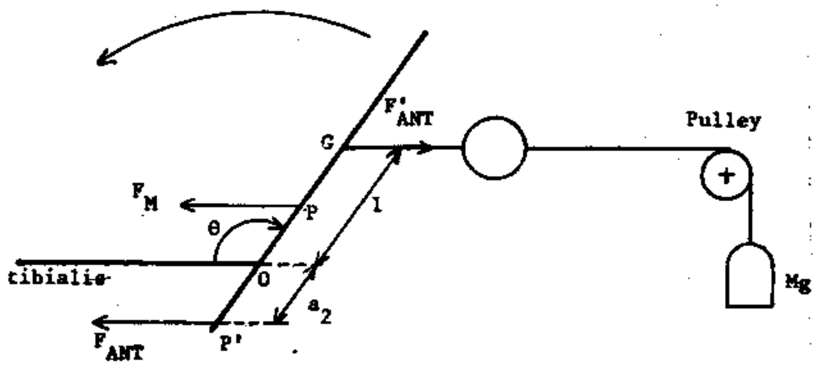


Figure 11 : Measurements of the passive effects F_{ANT}

We can write :

$$F_{ANT} = \frac{1}{a_2} F'_{ANT}$$

That is to say, carrying back this expression in equation (1) :

$$\ddot{\theta} = \left(\frac{a_1}{J} F_M - \frac{1}{J} (Mg + F'_{ANT})\right) \sin\theta + mg \frac{1}{J} \cos\theta - \frac{\xi}{J} \dot{\theta} \qquad (2)$$

Then, if the passive effects are brought back to the point of application of the external load, the unknown factor a_2/J is removed. The variation of F'_{ANT} as a function of θ shows a hysteresis effect (figure 12). The upper branch of the cycle corresponds to the raising of the foot (antagonistic group extension) and the lower branch corresponds to its lowering.

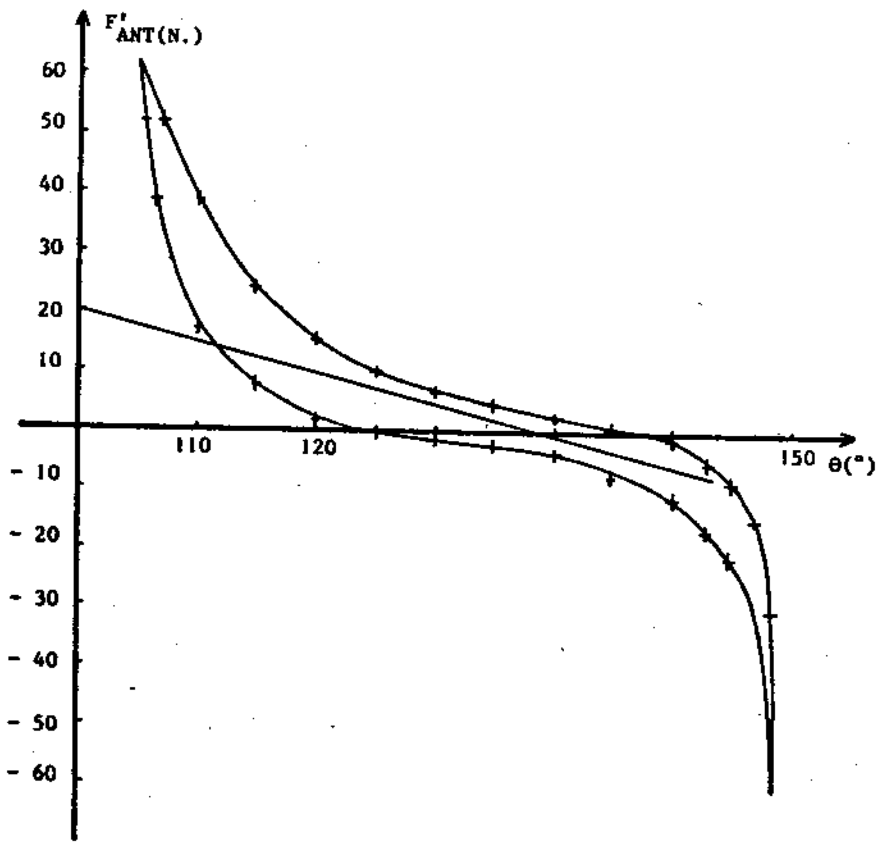


Figure 12 : Passive effects F'_{ANT} as a function of θ

IV - 3 Experiments with the muscle alone

This kind of measurement is intended to identify the muscle itself, that is to say to obtain the relationship V_{MOD} - F_M. The tendinous transducer which would be able to resolve this problem, has been abandonned because of, as already mentionned, the surgical difficulties encountered and the inaccurate results that it provided. We then dissociated the agonistic muscular group and the free lever. A dynamometer ring was hitched on the tendon. To maintain the same measurement conditions as in anisometric mode experiments the force transducer comes under a stress the value of which is the same as the initial force developed by the muscle when the tendon is not cut and when the free lever is subjected to an external torque Mgl. Finally, the stimulating signals must have the same characteristics as in the anisometric mode.

V - Conclusion

Besides the measurements of the position θ as a function of the modulation voltage V_{MOD} and the external load M, these three kinds of experiments lead to an evaluation of the biomechanical variables F_M and F_{ANT}, i.e. the force developed by the stimulated muscular group and the passive effects of the unstimulated one. The measurement of the parameters a_1, l, ξ and J depends too much on the experimental subject and is not accurate enough to be performed easily. We have thus chosen to compute them by an identification procedure.

We think that the experiments in the anisometric mode should be sufficient to characterize the system. Indeed, the relations F_M (V_{MOD}) and F'_{ANT} (θ) are identical from one subject to another, except for the gain which has to be adjusted according to the subject. An identification, followed by a simulation procedure should allow the evaluation of the unknown terms of the chosen joint.

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