A COMPARISON OF THE RESPONSES ON EXTERNAL STIMULATION OF THE HUMAN EXTREMITIES SKELETOMUSCULAR SYSTEM AND THE MODEL SIMULATED ON AN ANALOG COMPUTER

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Summary

In this study an analog model of the human arm has been compared to the arm of a live subject. The purpose of this comparison is the evaluation of similarity between the model and the live subject. In order to increase the similarity, simultaneous stimulations of the model and the subject were carried out. Parameters of the general model were adapted to the special characteristics of the live subject. The possibility of synchronous working of the analog computer and alive object is confirmed.

Introduction

Up to now several papers have been published that discuss problems of electrical muscle stimulation and simulation of human motion control systems, as well as of analog simulation of human extremities. There are only a few papers that treat all these three elements together and their interaction.

In this study an analog model of the human arm was compared to the arm of a live person. In order to increase the similarity, simultaneous stimulations of the model and the subject were carried out. Parameters of the general model were adapted to the special characteristics of the live subject. The possibility of synchronous operation of the analog computer and the live subject is confirmed.

Method

Both the object and the model have been working in close-loop feed-back connection with two identical controllers. The adjustment of model parameters was the aim of the experiment in

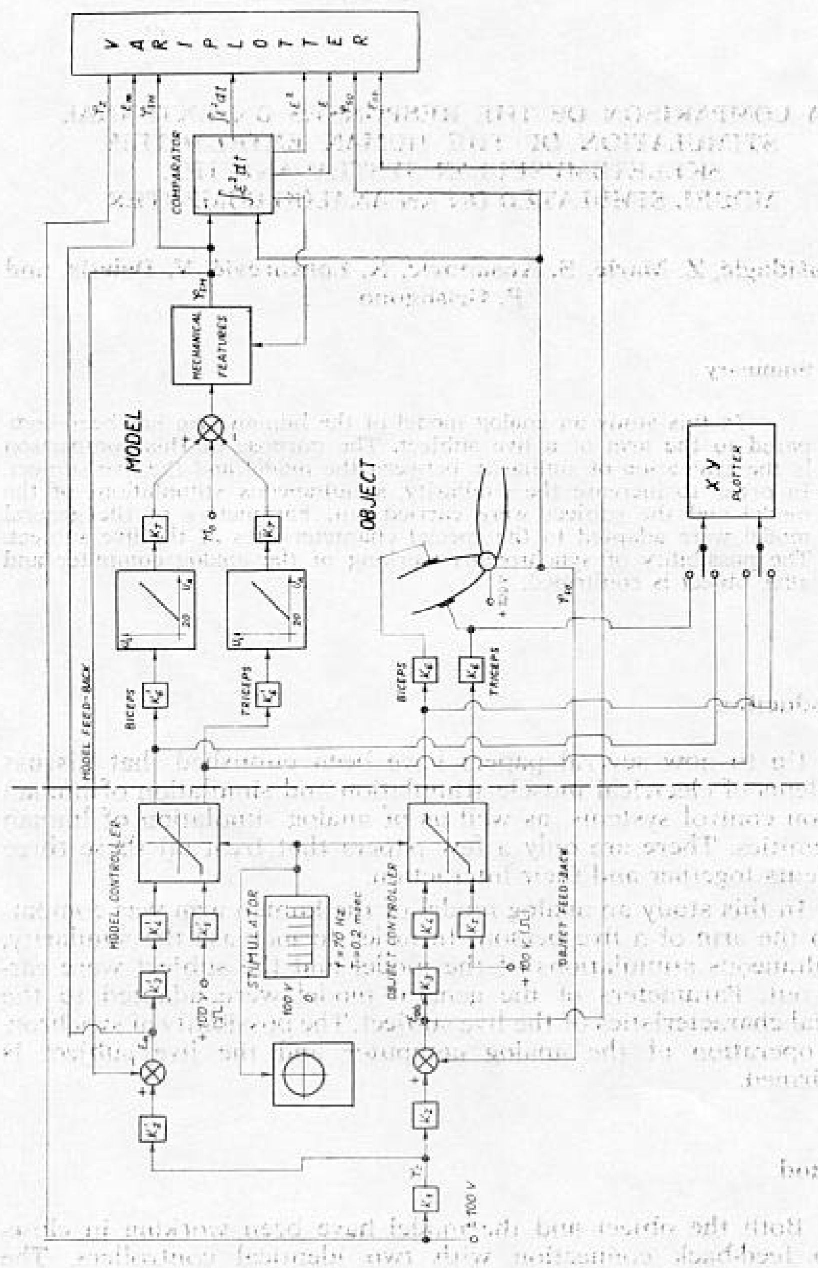

Fig. 1. General block diagram

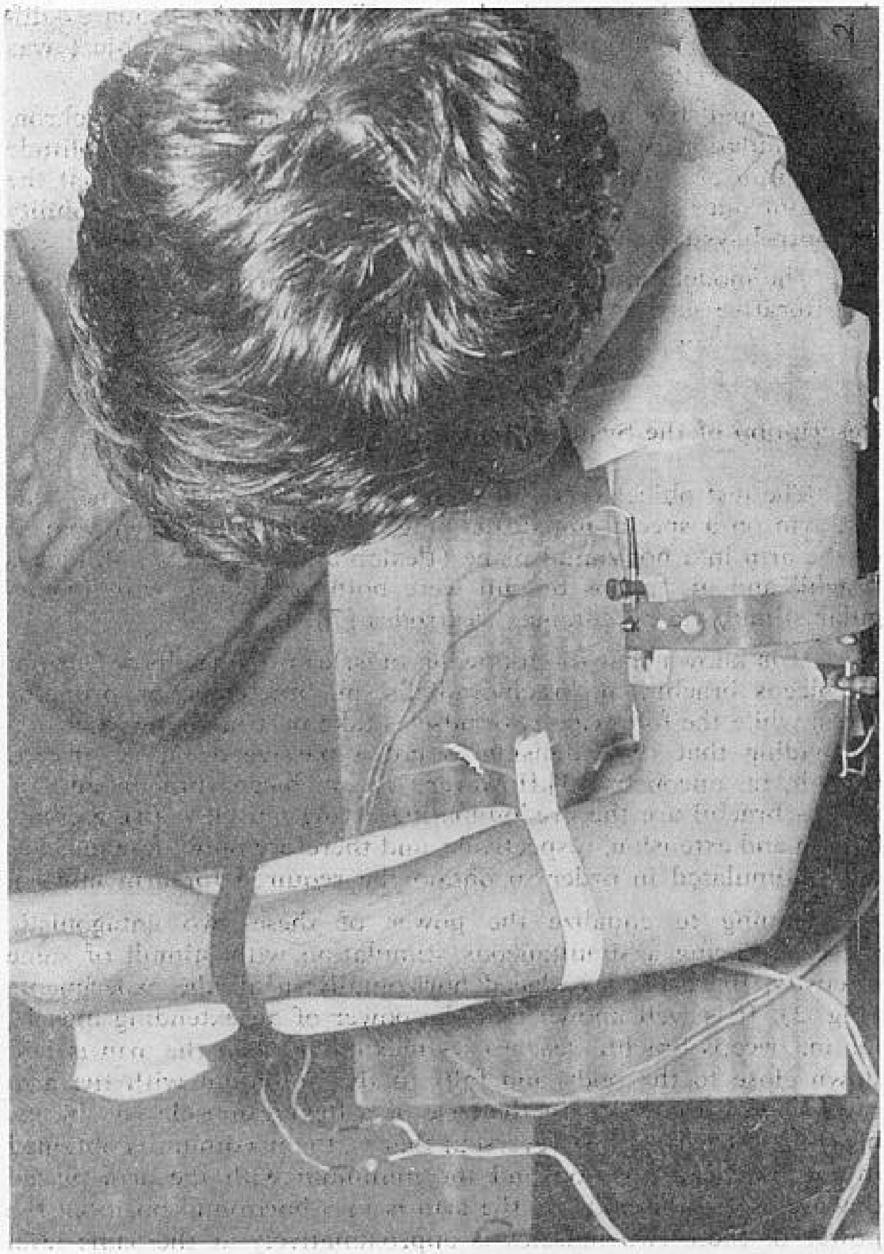

Fig. 2. Neutral arm position

order to decrease the error produced by the dynamic behaviour of the model in relation to the human. The integral of squared difference between the responses of the model and the object was chosen as a criterion of minimization.

Original structure of the controller was adapted with synchronous stimulation of antagonistic muscles and continual amplitude modulation of stimulation impulses. It was demonstrated that the new controller had more favourable features in regard to stability of control system than the designs reported so far [5].

The model parameters adjustment was carried out by manual and iterative setting of coefficients on the potentiometers.

Description of the System Components

The test object was a male person, 24 years old, who held his left arm on a special apparatus (Fig. 2) which allowed movement of the arm in a horizontal plane (flexion and extension). M. biceps brachii and m. triceps brachii were both stimulated with rectangular stimuli via percutaneal electrodes [7].

It is known that the following muscles provide elbow flexion: m. biceps brachii, m. brachioradialis, m. brachialis, m. pronator teres; while the following two muscles take part in elbow extension (providing that the extension is not a passive one): m. triceps brachii, m. anconeus [3].However, the m. biceps brachii and m. triceps brachii are the predominating acting muscles during elbow flexion and extension, respectively, and therefore only these muscles were stimulated in order to obtain the required forearm motion.

Aiming to equalize the power of these two antagonistic muscles, during a simultaneous stimulation with stimuli of same intensity, the arm was placed horizontally in all the experiments (Fig. 2). It is well known that the power of an extending muscle, i.e. m. triceps brachii, reaches its maximum when the arm is laid down close to the body and falls to the minimum with the arm raised above the head. In the case of a flexing muscle (m. biceps brachii), the case is just reversed; that is, the maximum is obtained in the overhead position and the minimum with the arm placed down close to the body. If the arm is in a horizontal position, the power of these two muscles is approximatively at the same level [6]. The horizontal position is attained, when the elbow bone (ulna) is turned towards the ground and with the radial bone (radius) faced to the opposite side, i.e. in upward direction.

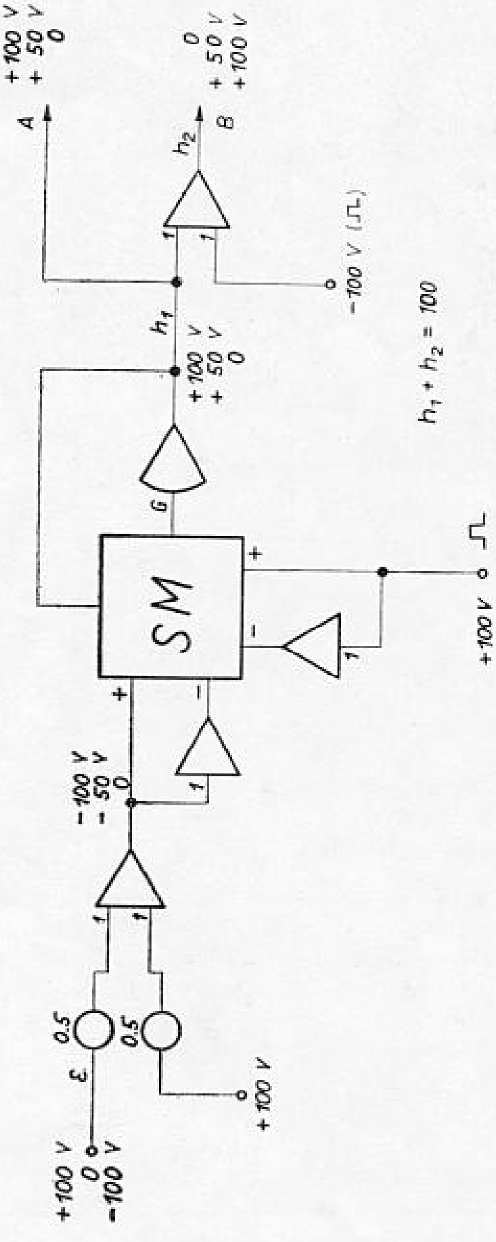

Fig. 3. Controller

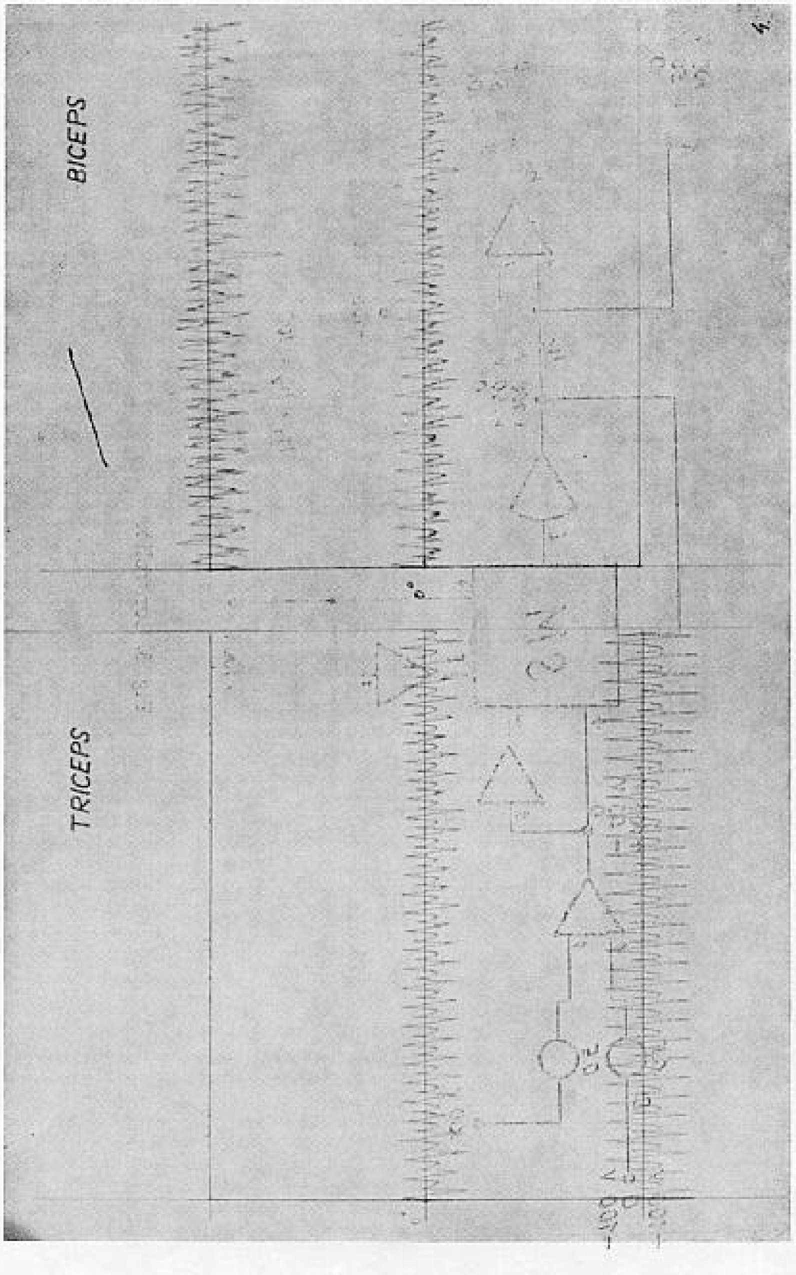

Fig. 4. Stimuli applied on muscles; $\varphi_{ch}=0^\circ$; $\varphi_r=+90^\circ, 0^\circ, -90^\circ$

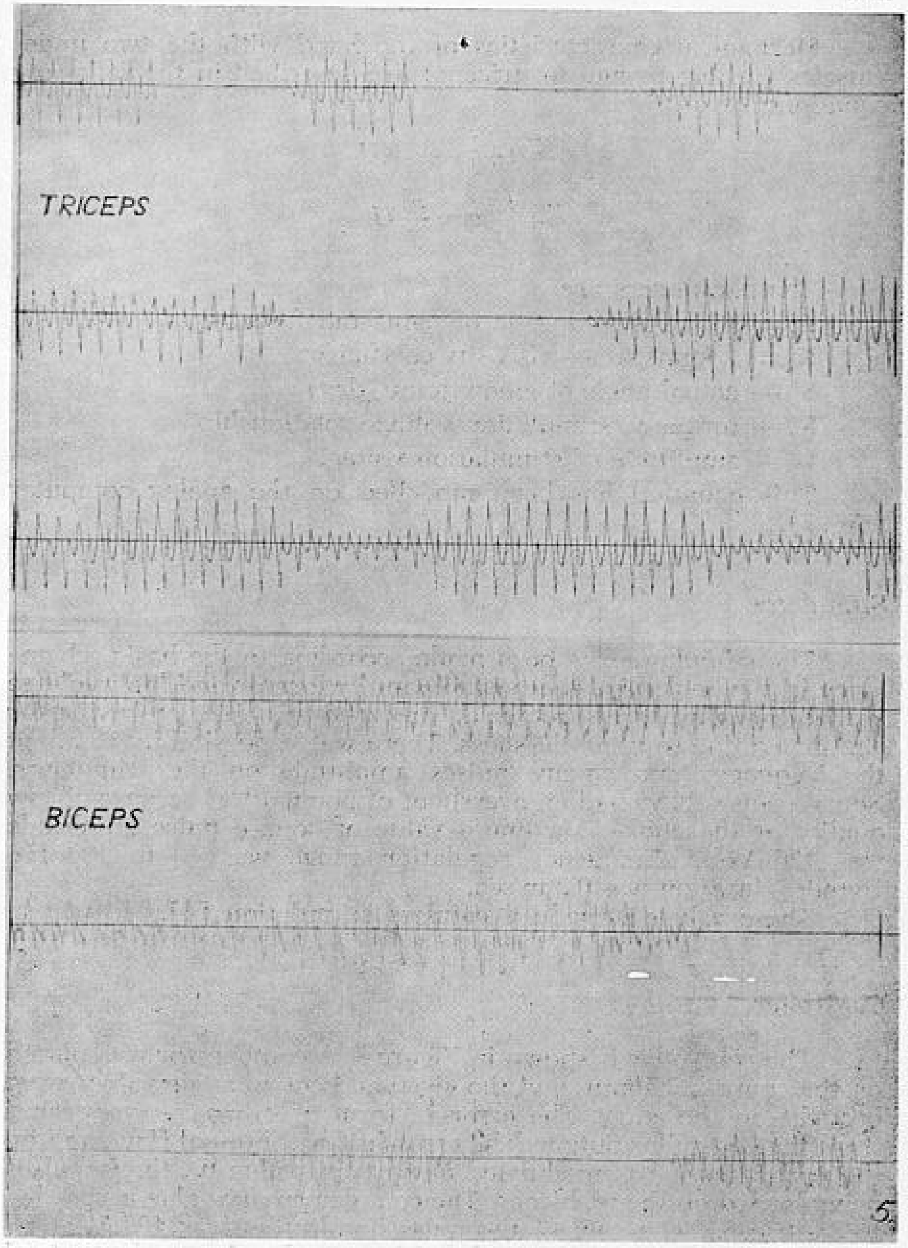

Fig. 5. Stimuli applied on muscles; $\varphi_e = +90°, 0°, -90°$; $\varphi_{ob} = \mathrm{var}$.

Model

Mechanical characteristics of the hand with the two upper muscles (m. biceps and m. triceps) are described in the following equation:

$$\ddot{\varphi} J + \dot{\varphi} K_s = KU$$

$$\ddot{\varphi} + \frac{K_s}{J}\dot{\varphi} = \frac{K}{J}U$$

The parameters are:

J $=0.09$ kgm^2 — inertia of hand and forearm

$K_s = 1.2$ kgm^2/sec — viscosity coefficient

φ — actual angle of elbow joint (deg)

K — torque v. stimulation voltage relationship

U — amplitude of stimulation voltage

This equation has been modelled on the analog computer (Fig. 7).

Stimulator

The stimulator has been made according to the basic scheme given in the book [4]. The unstable multivibrator and high voltage modulator have been retained, and the bistable multivibrator eliminated due to its uselessness. There was a possibillity to adapt the frequency and square pulses amplitude on the stimulator. Square pulses have had an overshoot of about 10%, because of low quality of the choke. Maximum value of square pulse amplitude was 120 Volts. Frequency regulation range was 40 to 100 Hz. Impulse duration was 0.2 m sec.

These values provide a painless stimulation [4].

Controller

The controller is shown in Figure 3. A comparator was placed on the controller input, and the given and actual angle values were brought on the entry. The error in form of $\varepsilon_{ob} = \varphi_{ob} - \varphi_{r}$ appeared from the controller output. The error had a continual flow, and on the multiplier it has modulated an impulse value h_1, the impulses being loaded on the m. biceps. The complementary value h_2 was led to m. triceps. The sum of the pulse amplitudes was 100 V at all times ($h_1 + h_2 = 100$ V). When the object reaches its predetermined angle, the controller sends equal amplitudes to both the m. biceps and m. triceps, and the arm is stopped. For the corresponding error values, the amplitude values on the muscles may be seen on Fig. 3.

The stimuli are shown in Figure 4, as they were generated in the controller and brought to each particular muscle, the feed-back connection was broken off. The arm was placed in a neutral position, that is $\varphi_{ob}=0^{\circ}$.

For maximal flexion, when $\varphi_{z}=+90^{\circ}$, the controller gives maximum amplitude of 100 V on m. biceps, but there is no stimulus on m. triceps. With the arm placed in neutral position ($\varphi_{ob}=0^{\circ}$) and the ordered angle is $\varphi_{z}=0^{\circ}$ the controller sends the same stimuli towards both the m. biceps and m. triceps, the amplitude being 25 Volts. In the same way, when $\varphi_{ob}=0^{\circ}$ and $\varphi_{z}=-90^{\circ}$ the m. triceps is stimulated with the maximum impulses. Deformity of the stimuli is a result of a slowness of recording and of the comparing process between the signals generated in the stimulator and those received with a delay from the multiplier. On Fig. 5, the controller action may be seen, when the $\varphi_{z}=\text{const.}$ and φ_{ob} is changed, the latter is $+90^{\circ}$, 0° and -90° alternatively. On recording of these controller characteristics, the feed-back connection has been broken off.

The model controller works the same way as the subject controller.

Course of the Experiment

Block diagram of the complete experiment is given in Figure 1. Both the subject and the model were stimulated each one through its own controller with the pulse values of h_1 and h_2. Coefficients K_4 and K_4' are 0.5 and they reduce the h_1 and h_2 amplitudes down to 50 V. At this amplitude the full tetanic contraction has been obtained.

The subject's response is represented by the φ_{ob}, and the response of the model by the φ_{m} value. The responses were compared and the system error emerged as $\varepsilon=\varphi_{ob}-\varphi_{m}$. The error was squared and integrated, and the final result brought to the 8-channel recorder. Beside these three values, the following ones have been recorded: given angle value (φ_{z}), subject response (φ_{ob}), subject error ($\varepsilon_{ob}=\varphi_{ob}-\varphi_{z}$), model response ($\varphi_{m}$) and model error ($\varepsilon_{m}=\varphi_{m}-\varphi_{z}$).

On Figure 6, the circuit for the subject and its controller is shown in detail. The latter was set up on the analog computer. Coefficient K_4 is established by the P10 and P11 potentiometers.

Figure 7 represents all the components of the model and its controller, as they were placed on the machine. Coefficient K_4' is fixed by the Q35 and Q37 potentiometers. The complete experimental set-up is given in Figure 8. Both the subject and the model were stimulated by the same rectangular pulses from the stimulator simultaneously. The starting point of the arm and the model was established in neutral position $\varphi_{ob}=\varphi_{m}=0^{\circ}$. At a moment of $t=0$,

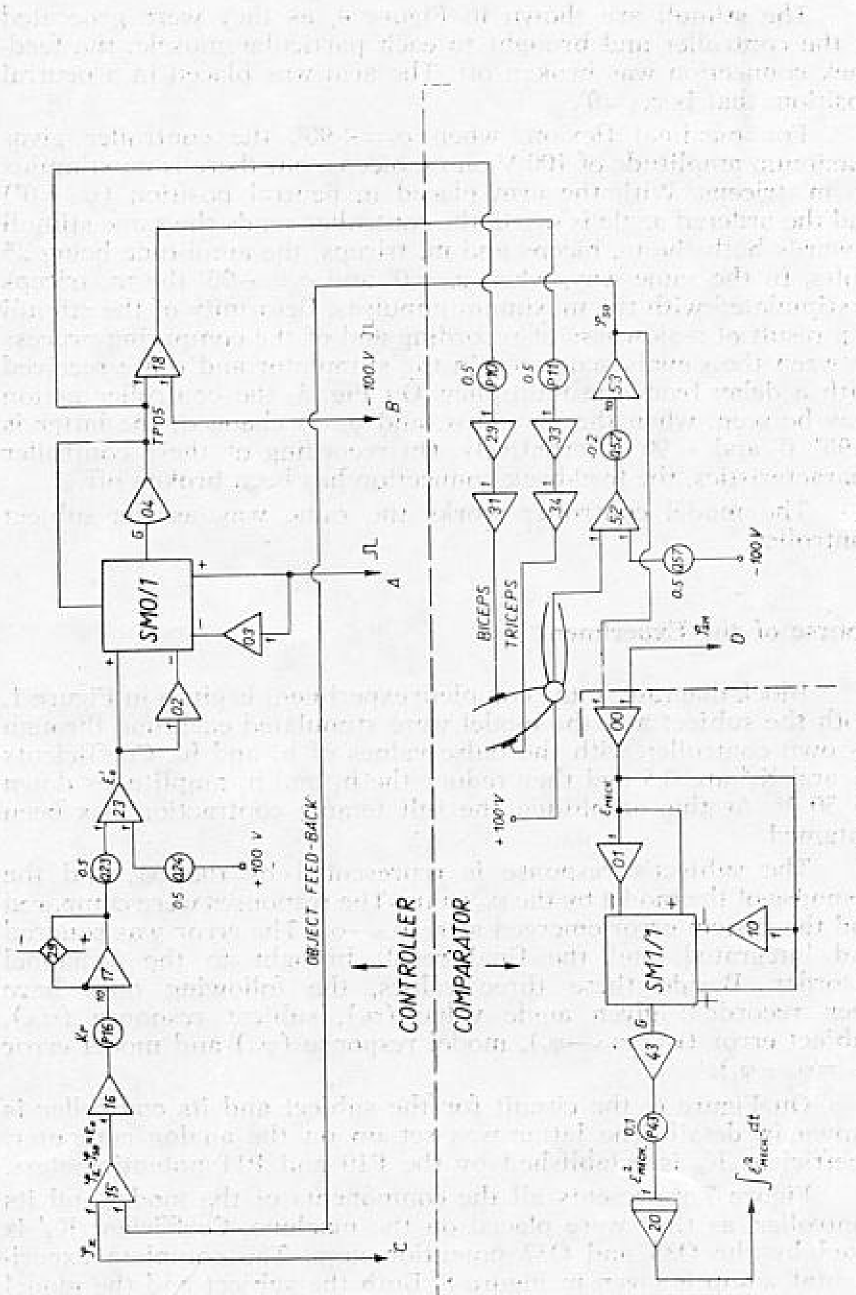

Fig. 6. Object and its controller

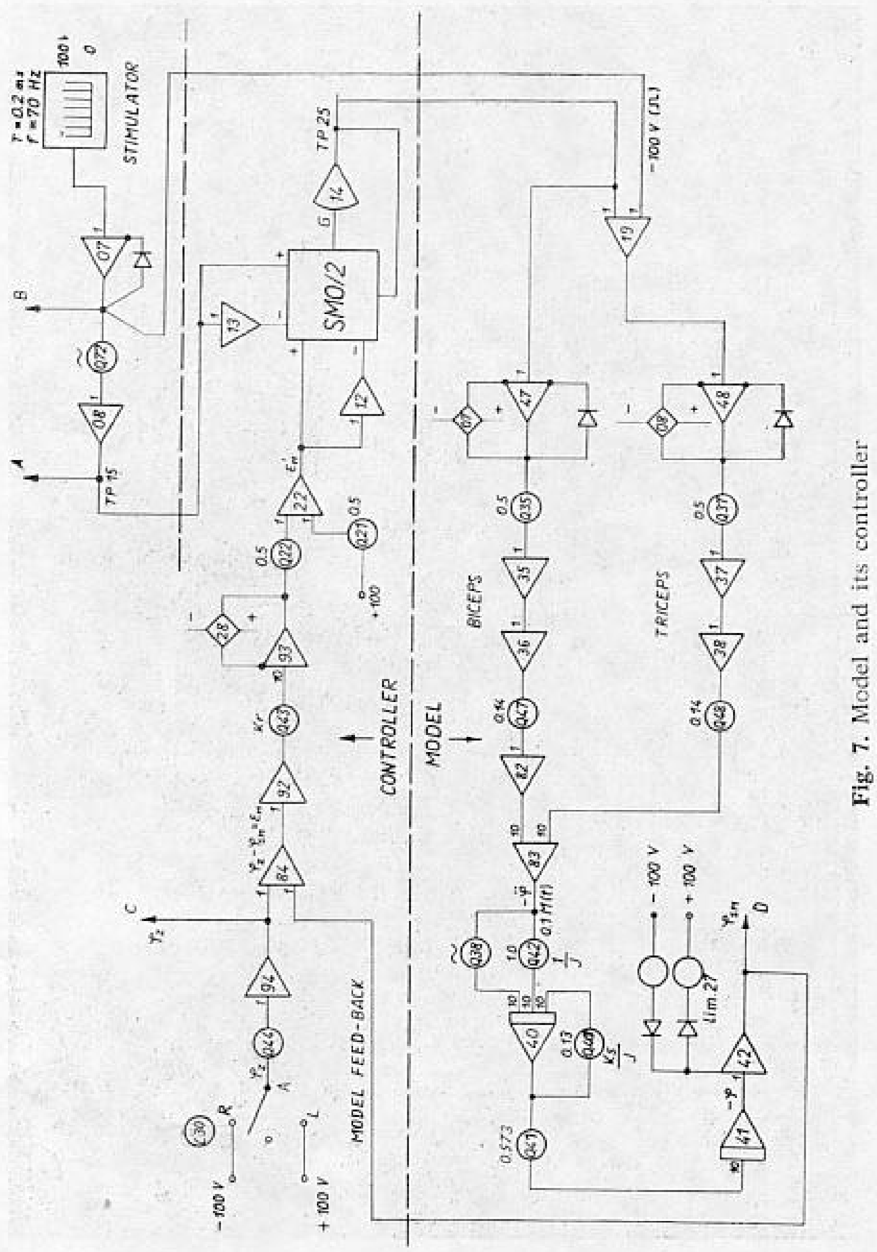

Fig. 7. Model and its controller

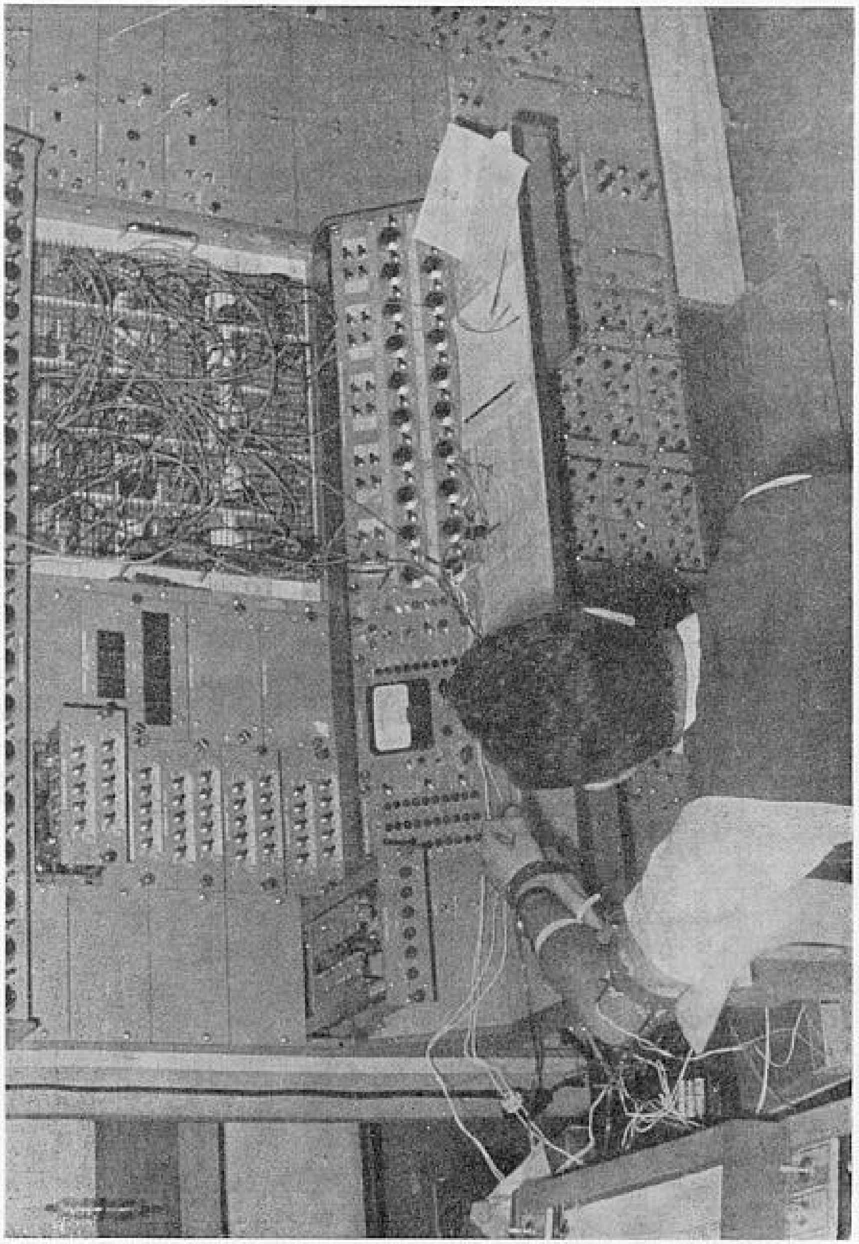

Fig. 8. Experimental set-up

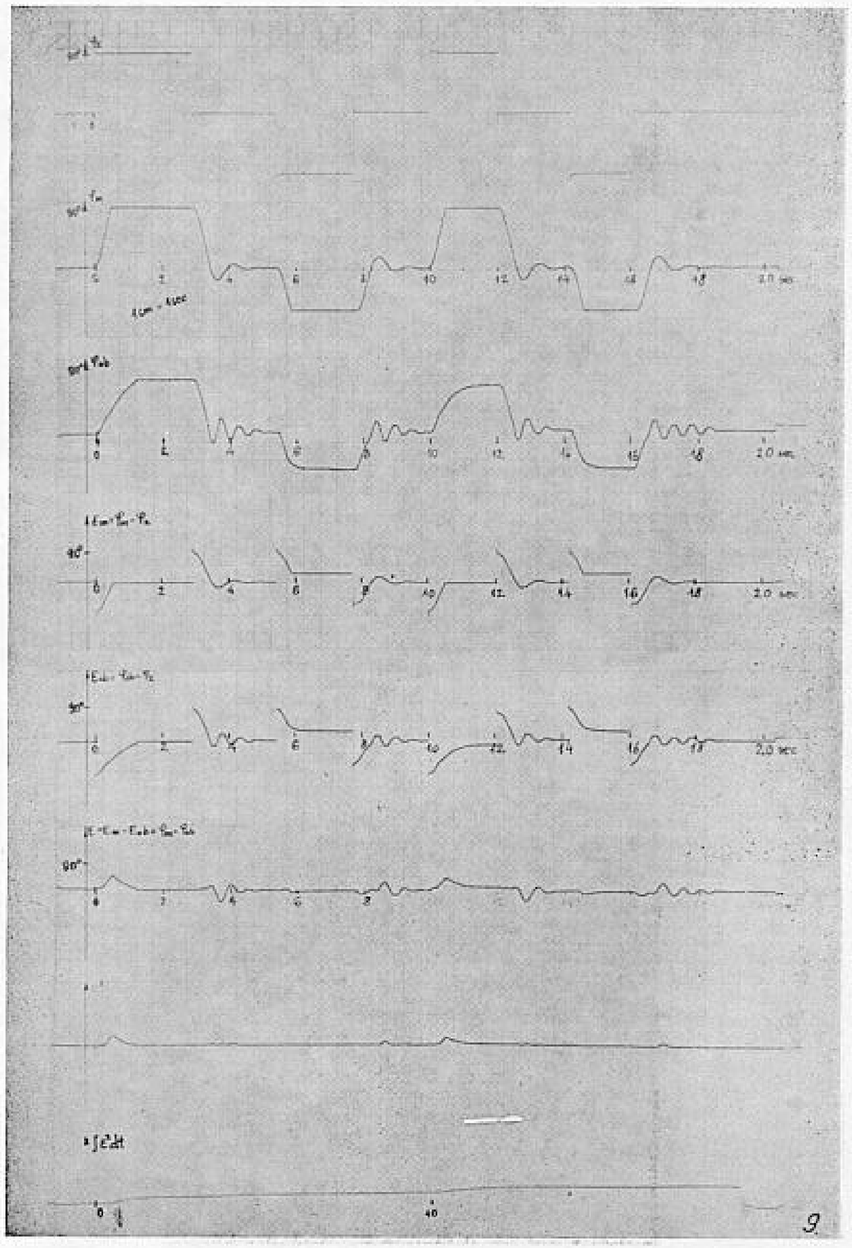

Fig. 9. Time course of responses before adjustion

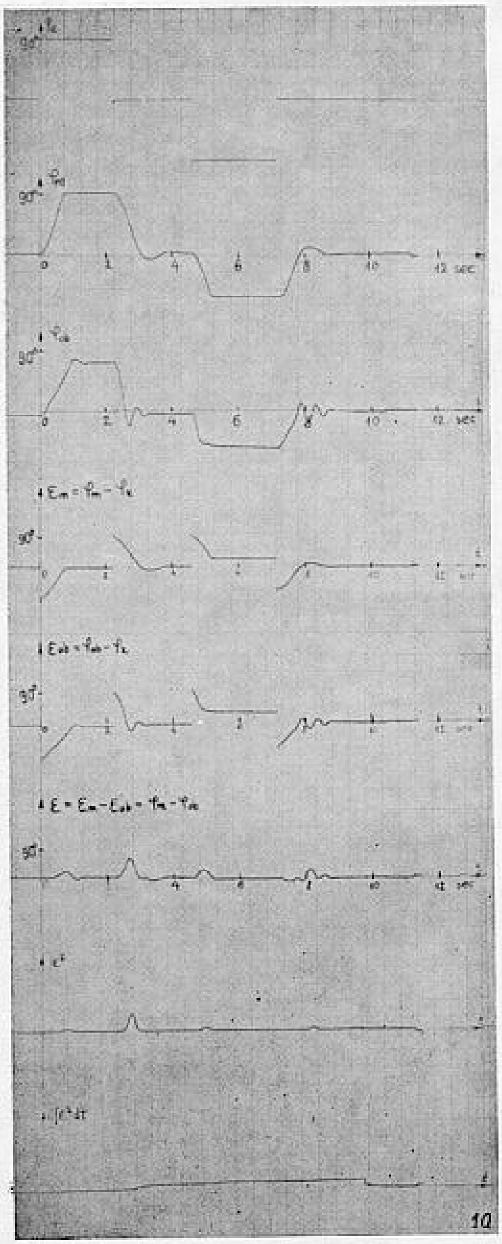

Fig. 10. Time course of responses after adjustion

the $\varphi_r = +90°$ order was put on, kept constant for about 2 seconds, returned back to the zero, then overturned to $\varphi_r = -90°$, kept for 2 seconds again, and finally returned to zero value.

The time course diagram (Fig. 9) displays the changes of all the values recorded on the 8-channel recorder (Variplotter). In this case some coefficients were approximitively set up on the machine in accordance with an early experience. The similar diagram (Fig. 10) shows the changes of the same values after adjusting of the coefficients mentioned before.

Results and Conclusions

On the diagrams (Fig. 9 and 10) the same results are shown, as they have been recorded before and after the adjustment. The 8th channel on the figures represents the tracing of the squared error integral value, which is a criterion for the model fidelity evaluation. For example, at the 10th second of the time course it may be seen that the integral has a smaller value when the model is adjusted, i.e. the function adjusted model is more similar to that of the subject.

In summary we wish to point out:

— we have modelled a biological system on an analog computer;

— the experiments were carried out with an "on-line" connection between the machine and our live subject;

— the flexion and extension, obtained from the stimulated arm were both very similar to those during a physiological movement. We have been able to change the duration of the arm flexion and extension;

— we tried to make an identification of some parameters of the analog model by different methods, ranging from purely manual to fully automatic setting or so-called "self-adapting" of the machine.

All these operations were performed in order to obtain a quite feasible and useful method for construction of musculoskeletal system models, suitable for some experiments in the field of physical rehabilitation.

We believe that a higher fidelity between a model and an object might be obtained by using a fully automatic and continually adjusting process in regard to the coefficients mentioned before.

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Practical part of the study has been carried out in the Computer Center of "Energoinvest" — Sarajevo. An EAI's analog computer PACE 231R was used.

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