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CORRECTION BY ELECTRICAL STIMULATION OF MUSCLES SOME ELEMENTS OF WALKING OF THE PATIENTS SUFFERED FROM CHILDREN'S CEREBRAL PALSY

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Abstract

Electrical stimulation of muscles during walking is one of the methods of increase of motor function of the patients with children's cerebral palsy (CCP).

Some biomechanical investigations have revealed significant disorders of kinematics and dynamics of walking the patients with CCP. The type and parameters of stimulating signals providing painless effective muscle contraction have been established by means of the analysis of possible kinds of electrical signals and their evaluation on the basis of criteria being worked out.

Parameters of stimulating electrodes and their interrelationship with anthropometric characteristics of patients have been established. By means of possible ways of gathering information about step phases on the basis of precision criterion advisability of usage of an interlinked angle transducer has been determined for synchronization of a moment of supplying stimulating signal with a step phase.

The results of application of electrical stimulation of muscles during walking of patients with CCP have been estimated by objective methods.

At present numerous attempts are known on creation of artificial systems of control by the work of internal human body organs and skeletal musculature with usage of an exciting action of an electric current.

The possibility of using artificial control systems for restoration of the function of paralyzed muscles is a matter of a great interest. Such tasks rise in particular in the case of children's cerebral palsy (CCP).

The problem of a gait correction of these patients is extremely urgent because of a large number of patients with CCP and a limited store of means of their rehabilitation. The paper for the first time raises a problem of a gait correction of the patients with CCP.

The correction of movements by the method of a functional electrical stimulation (FES) is known to be the most reasonable into the swing phase /1/.

As the movements at the ankle-joint during swing phase are not so important as the movements at the knee-joint, and changes of an amplitude of movements and of angular speeds at the hip-joint of the patients with CCP are rather small, the problem of correction the movement of extension at the knee-joint during swing phase of a step was considered as the most significant. It is worth to note that increase of extension at the knee-joint up to the moment of a stance promotes reduction of total energy expenditures during walking /2/.

For correction of extension at the knee-joint during swing phase an application of additional forces is required. It is supposed that these forces can be provided at the result of contraction of the extensors of the shank with the action of an external electrical excitation on them. Correction of the movement under the action of these forces is possible only in that case if they have a sufficient value and are applied at the required time intervals. In such a way the problem of a movement correction is preceded by the problem of getting of a necessary force of a provoked muscle contraction.

As to the point of view of the theory of automatic control the problem of a movement correction by means of an electrical stimulation consists in the creation of such a controller with the help of which it could be possible to provide normalized movements /fig.1/.

As the data on the application of FES devices for the patients with the CCP are absent, first of all it was necessary to clear up the following: a) the fundamental possibility of a local (without irradiation), effective, provoking a certain effort, sufficient, for example for extension at the knee-joint, painless interaction of an electric excitation on the lower extremity muscles affected with the CCP; b) the fundamental possibility of interaction on the volume and the speed of the movement at the knee-joint by means of an electrical excitation of the muscles.

As a result of investigation of 55 patients with the CCP above-mentioned questions have been settled positively.

With the correction of extension at the knee-joint the object of control is a shank. As the features of the correction object are not known the total task is fractioned into some private tasks.

The foremost task is determination of a necessary type and parameters of control commands U(t). Known up to date theoretical and experimental data on the properties of a muscle and a neural-muscular apparatus as the control object, as well as information about kinds of signals which can be used for the FES don't allow to choose the type and parameters of control commands.

The analysis carried out and classification of the possible kinds of control commands have shown the necessity of studying the reasonability of application of the correction system the control commands of a random character - a bioelectric signal - and of a determinate character: 1) continuous, amplitude-modulated sinusoidal signal. 2) discrete signal as a train of square current pulses.

For carrying out investigations and with the purpose of grounding the structure and parameters of a correction system special methods have been worked out /3, 4/.

Selection of control commands of a correction system was performed on the criteria which have been worked out. These criteria can be divided into three groups: functional, technical and physiological. The patients with CCP for whom the

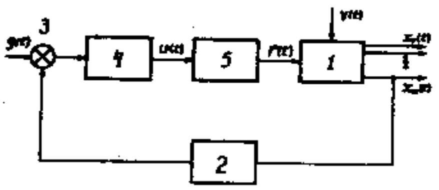

Fig. 1

A structural diagram of a correction system for extension at the knee-joint:
1 - the object of control (the shank); 2 - a measuring member; 3 - comparator; 4 - a controller (stimulator); 5 - an actuator (muscles-extensors of the shank).

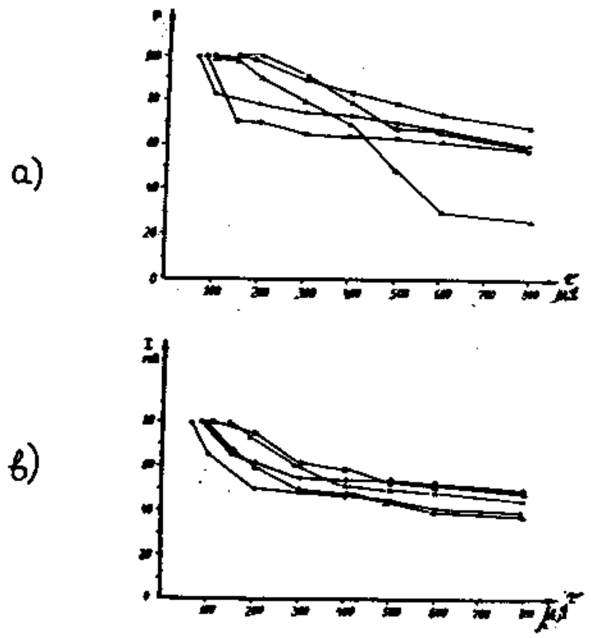

Fig. 2

a) Dependences of a maximum value of an exerted moment of a force upon the current pulse length (a repetition frequency of pulses is 50 pulses/sec).
b) The borders of a comfort zone under the action of a current pulses.

system if provided, will use it only in that case if the influence of the system does not cause unpleasant feelings. So one of the main requirements which control commands must meet is the requirement of a comfort.

One of the functional criteria of selection of the control commands type may be a maximally possible value of a developed force moment which determines potential resources of different type commands. The other functional index is the time of transitional processes when supplying the control commands of different type and parameters onto the actuator and when picking-up them off the actuator. The parameters of the commands which provide getting maximum force moments, make an opportunity to evaluate some technical characteristics, e.g. an expendable energy, the size and the weight of the device and of a power supply.

It is necessary to take into account specific properties of the actuator - a living muscle, which is connected with its nature. It is known that muscular force evoked by electrical stimulation decreases gradually as a result of developing fatigue. Evidently, that for practical use the commands providing a sufficient moment of a muscular contraction force, provoking with it the least fatigue, arouse the greatest interest. The selection of the type and parameters of control commands was performed in consideration of above-mentioned indices on the base of experimental data.

Comparative investigation of sinusoidal amplitude-modulated and square control commands was performed for 5 normal patients and 20 pathological cases of disease by CCP with a moderate degree of affection.

Control commands were used as a train of square current pulses corresponding to the border of a comfort zone. The results of investigation of the actuator output characteristics in norm and pathology have shown that the greatest moment of a muscular force was provided while using the pulses with a length from 30 up to 350 microseconds, the amplitude of 65 mA (milliampere), the frequency of 40-50 Hz /fig.2/. Increase of the pulse length up to 1,000 microseconds reduces a maximally possible force moment on an average to 50 per cent from a maximum moment which corresponds to above-mentioned lengths.

Investigation of a sinusoidal amplitude-modulated signal has shown that the greatest moment of muscles-extensors of the shank is provided if a carrying frequency is at the range of 3-8 Kc/s (kilocycles per second), a modulation frequency is at the range of 80-160 Hz, voltage amplitude is not more than 30 V /fig. 3/.

The ratio of maximum force moment values exerted by the extensors of the shank with voluntary development of the effort and under the action of the commands in the form of a square and a sinusoidal signal is 1 : 0.58 : 0.46 for the norm and 1 : 0.65 : 0.41 for the patients with CCP /fig. 4/.

Investigation of a fatigue development process /fig. 5/ has shown that when using a sinusoidal amplitude-modulated signal, the decrease of a force moment during 300 second is 60 per cent from a maximum one. During the same time the decrease of a force moment with voluntary development of the effort and under the action of a pulse train is 30-40 per cent from a maximum.

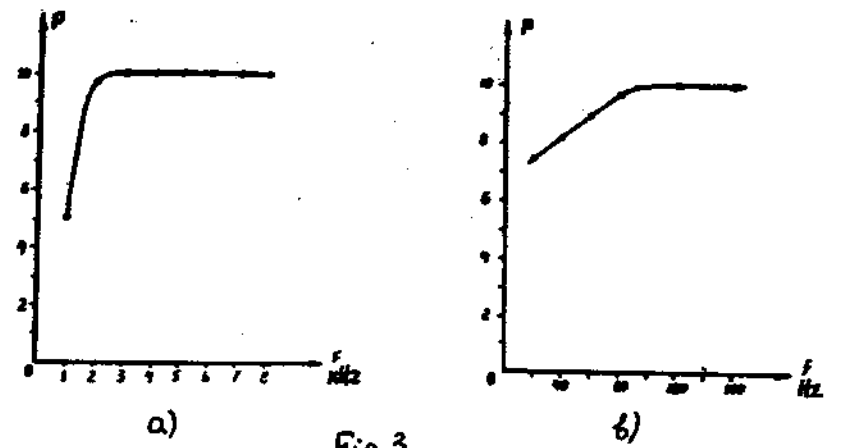

Fig. 3

Dependence of a value of a force moment exerted by the muscles-extensors of the shank upon the parameters of control commands in the form of a sinusoidal signal:

a) upon the frequency of carrying signal at the frequency of modulating signal equal 100 Hz;
b) upon the frequency of modulating signal at the frequency of carrying signal equal 3 KHz. The depth of modulation is 100%.

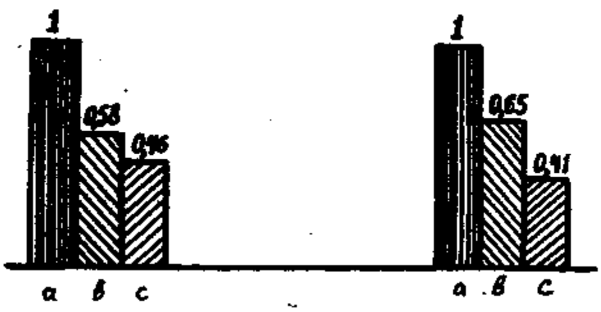

Fig. 4

The ratio of the values of maximum force moments, exerted a) with a voluntary development of the effort; b) under the action of a train of current impulses; c) under the action of a sinusoidal amplitude-modulated signal. From the left - is a norm; from the right - in pathology.

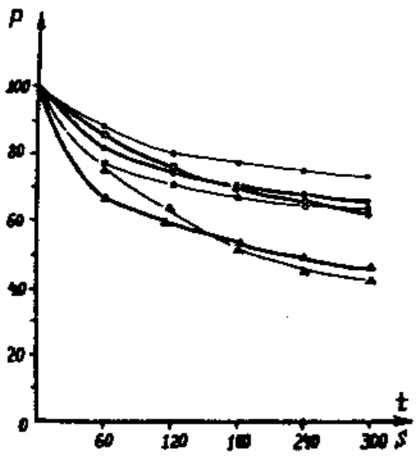

Fig.5

The process of a fatique development

— - norm

— - pathology

• - at a voluntary development of a moment

o - under the action of stimulating square current impulses

Δ - under the action of a sinusoidal amplitude -modulated signal

It is worth to note that with the same moment of the force the energy of a sinusoidal signal almost two orders outnumbers the energy of a pulse train /5/.

When using an impulse signal it is possible with simple means to provide efficiency, reliability and stability of a correction system.

Investigation of a possibility of using the bioelectric activity as control commands has revealed the measured values of the bioelectric signal parameters (an average length of the pulses, an average frequency) to be sufficiently differed from those ones which provide an effective contraction of the muscles.

As the frequency of a pulse formation of a bioelectric signal varies, it should be awaited of significant fluctuations of a force moment when using this signal as a control command. The experiments have proved out above-mentioned conclusions and have revealed unreasonability of application of a muscle electrical activity as control commands in the systems of a movement correction.

Thus, at the result of research the reasonability of application of the control commands as a sort of a train of a current impulses has been proved for the correction system, the control with a muscular force moment value being carried out by changing the length of pulses.

Weis's law was used for the evaluation of efficiency of different length impulses. Weis's law inderlines the connection of a threshold length of a single current impulse with its amplitude $i = \frac{a}{\tau} + b$, where i - is the current of an impulse, τ - is the length of the impulse; a, b - are the parameters, characterizing the properties of an evoked tissue. Let Q - is the value of a charge which is transferred by the current impulse of the length T (fig.6).

Evidently $I \cdot T = Q$

The charge, exceeding the threshold value Q_{exceed} is equal $Q - I \cdot t$, where $t = \frac{a}{I-b}$

In consideration of the Weis's law it is possible to prove that $\lim\limits_{T \to \frac{Q-a}{b}} Q_{exceed} = 0$, as well as $\lim\limits_{T \to 0} Q_{exceed} = Q - a$

At the interval $0 < T < \frac{Q-a}{b}$ the derivative $Q'_{exceed} = -\frac{abQ}{(Q-bT)^2}$ does not turn into 0, so the function Q_{exceed} is a monotonously decreasing one at this interval, and is limited from above by the value $Q - a$, and from below - by the zero. Thus it may be supposed that short pulses would be more effective than long pulses carrying the same charge.

Weis's law is true for single pulses. However is may be supposed that to some extent the obtained data would be true and for a train of greatly spaced pulses. The experimental data which had been received prove this thought and show that pulses of a less length and/or a larger amplitude carry a less charge than a train of pulses of a larger length. In this case the greatest moment of the force of the below-knee muscles-extensors is provided.

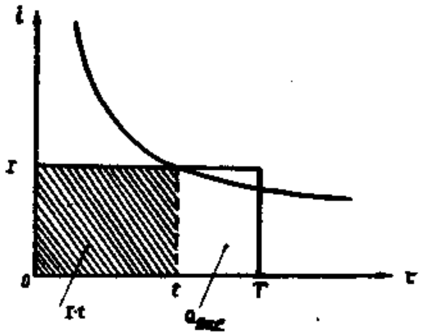

Fig. 6

Determination of the efficiency of the impulse action by means of the Weis's law.

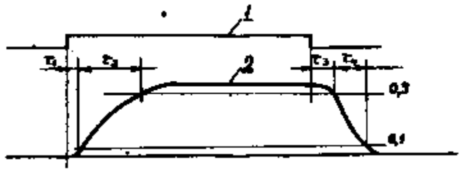

Fig. 7

Determination of transient characteristics:
1 - disturbance action; 2 - a transient process.

The analysis of the results of the research of the electrode parameters has revealed the following. We have a reliable objective method for determination of the electrode sizes as well as the sides of their placement: at the systems of correction of extension at the knee-joint it is reasonable to use the electrodes similiar on their form to the rectangular ones, with semi-circular edges. The sizes of electrodes and the thigh perimeter, measured on the border of the middle and lower third, are closely connected.

This allows to determine the proper sizes of electrodes by a simple measurement of a thigh perimeter. An approximate relationship of an active electrode sizes is 0.4P · 0.1P, where P - is a thigh perimeter measured on the border of the lower and middle third.

The above-mentioned data on the type and parameters of the control commands, on the form and sizes of the electrodes were used for determination of the transitional characteristics /fig. 7/.

With development of a force moment by the extensors of the shank, under the action of a control command a pure time delay is τ_1= 60 microseconds and the time of a transient process is τ_2= 260 microseconds. With decrease of a force moment a pure time delay and the time of a transient process were relatively τ_3= 100 microseconds, τ_4=120 microseconds. The study of transient characteristics of the actuator (a muscle) together with the object of the control (the shank and the foot) has shown that τ_1 = 60-80 microseconds; τ_2 = = 160 microseconds. At voluntary control the time of a transient process is significantly longer - τ_2= 400-600 microseconds. Such data were considered as initial ones for the development of a correction system.

Thus the analysis of possible ways of building the systems of control by walking has shown, that a system the control by which is carried out using natural processes following human walking should be chosen as an initial model of a correction system for extension at the knee-joint.

The transient characteristics obtained for the correction object as well as biomechanical data on the walking of the patients with CCP testify to the reasonability of using the relay mode of the correction system performance.

For an effective work of a correction system of such a type its synchronization with the phases of a step is required. Different phenomena accompanying walking may carry the information about the phases of a step: a bioelectric activity and myotonic characteristics of the lower extremity muscles, some elements of the step (e.g. the beginning of the heel stance, the push-off the heel from the ground, the push-off the toe from the ground), kinematic characteristics of walking. The comparison on the base of a precision criterion of different ways of synchronization of the system correction performance for extension at the knee-joint with the phases of a step has revealed that using synchronization on the value of a knee angle for these purposes allows to reduce to zero an angle value variation on/when the correction system is switched on/ and eliminate its dependence upon the walking rate.

At the worked out one-channeled system of correction an angular synchronization transducer of an analogue type is used which performs triggering of the system at the required phase of a swing phase of a step.

At the output of the system the control commands formed as a pulse train. The weight of a model without a power source is 370 g, the sizes - 130 mm x 90 mm x 40 mm. When both of the legs are affected a two-channeled system [redacted] worked out for the correction of extension at the knee-joints was used.

The application of the correction system for extension at the knee-joint when walking the patients with CCP allowed to increase the angle β and the average velocity V of extension at the knee-joint up to the moment of touching the ground with a foot (table 1).

	β°	$\beta^\circ_{кор.}$	$\frac{\beta-\beta_{кор}}{\beta}$ %	α°	$\alpha^\circ_{кор.}$	$\frac{\alpha_{кор}-\alpha}{\alpha}$ %	$\frac{V_{кор}-V}{V}$ %
m	29	19	34	49	58	18	65
σ.	13	10	9	10	10	12	60

m - assembly average

σ - standard deviation

These effects are caused by a direct action of the correction system onto the extensors of the shank. However it is interesting to note and a side effect which consists in that for the response on a changed biomechanics of extension at the knee-joint of the patients, the angle α of flexion at the knee-joint was increased at the end of a stance phase, at the beginning of a swing phase. This served as a preparation for the extremity to a subsequent extension at the knee-joint under the action of the correction system.

In such a way a comparative study of a voluntary and corrected walking of patients with CCP has shown that the correction system suggesting an extension at the knee-joint improves kinematics and dynamics of the movements in this joint. At present finishing of the design is being carried out.

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