THE PROBLEMS OF CONTROL BY A BIOTECHNICAL SYSTEM " MAN-PROSTHESIS" WITH AN EXTERNAL ENERGY SOURCE

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Development of a functional prosthesis may be realized on the base of consideration of interrelationship of a biotechnical system" man-prosthesis" (BTS-MP). With this a problem arises on the study of a biological object - an invalid- aimed at its coupling with a technical device - a prosthesis- into an integrated biological system (N.Wiener,I). Taking into account complexity and originality of prostheses I.I.Artobolevsky in 1964 proposed to introduce a new class into classification of mechanisms which reflected interrelationship with biological objects (2). According to the definition given by V.M.Akhutin"a biotechnical system is an especial class of large systems representing an aggregation of biological and technical elements connected between themselves in a common loop of control" (3). According to this definition the main elements of BTS- MP should be combined with indicators of prescription, functionality and reliability. One of the most important elements of BTS-MP is " a man" which may be characterized by a number of parameters determined by the state of physiological systems of an organism, the degree of affection of a supporting-motor apparatus, the state of a stump, the age and sex, conditions of motional activity. A subsystem " prosthesis" has been considered from the standpoint of possibility of a prosthesis prescription, its functionality and reliability. The elements of BTS-MP are connected between themselves by a causative-corollary relationship (cause and effect connection), (Fig.I). A structural scheme of BTS-MP includes elastic, adjustment, intermediate and bearing elements which may be used in different combinations, levels of the prosthesis and are also determined by the indicators of prescription, functionality and reliability (Fig.2). But in real conditions of functioning the interrelationship of elements and subsystems of BTS-MP inside the system takes place not only between themselves but with the environment as well. The mentioned interrelationship depends on the road profile and the type of a road covering as well as other identic conditions. The character of interrelationship is estimated by the indicators of reliability of control by the prosthesis, and by interrelationship of a propelling agent with a road covering (Fig.3). As any other complex system is evaluated by a number of criteria, the same way a number of characteristics has been proposed for evaluation of functioning of BTS-MP : tolerance, harmony of movements with minimal energy expenditures of the organism while walking, safety, stability of maintenance characteristics of the prosthesis, controllability. According to the mentioned characteristics, the ways and means of their realization have been proposed (Table I).

Table I. The main characteristics of BTS " Man-Prosthesis"

Characteristic	Ways and means of realization of characteristics
Tolerance	Use of a rational suspension; optimal form of a socket; constructive versions of low-noise movable connections; use of materials not causing allergic reactions of organism; efficiency, simplicity and availability of a sanitary care means; anthropomorphic character of an external form, kinematic and dynamic characteristics
Harmony of movements at minimal energy expenditures of an organism during walking	Realization of motional functions; rational distribution of masses of the prosthesis links; recuperation of energy while walking; use of external sources of energy for reproduction of motive functions; use of prostheses of purposeful appointment, i.e. sporting, seasonal, domestic and other ones.
Safety	Resistance to bending at the stance phases of a step; stability against external influences; absence of toxic components in materials having a contact with a human body
Stability of characteristics of maintenance and exploitation of prosthesis	Reliability of the details and units of a prosthesis; guaranteed reserve of strength; anticorrosion stability against influence of physiological solutions; water- and dust-proof of elastic cosmetic coatings; stability of polimer and composite material properties in the programmed time intervals; their biological non-toxity (inertness)
Controllability	Optimal weight of prosthesis; programmed characteristics of elastic connections of the PL (prosthetic limb) links

The analysis and the synthesis of control in such a complex BTS-MP with its variety of connections is possible by different ways, for example, on the basis of formulation of equations of a system movement, presumably, the Hamilton or Lagrange equations of the second order, with a help of graphs and power flows, with use of chains, etc. A common disadvantage inherent in the mentioned methods is difficulty of their practical realization. It should be noted that in a modern theory of mechanisms and machinery one of the most effective methods for studying complex machinery is a grapho-analytical method (2). Nevertheless in establishing a law of control of biped gait this effective method at present is used in extremely limited volume. Apparently, realization of the tasks connected with control by movement of anthropomorphic mechanisms is mostly available with a help of a graphoanalytical method, in comparison with analytical methods as it is characterized by clearness and simplicity and may be recommended for solving a whole number of the tasks of an identic type.

In the work a graphoanalytical method is used for determination of the law of control by the movement of a lower extremity prosthesis with an external source of energy (EES). A motorized above-knee prosthesis provides a motive function, normalizes the character of push-off by the prosthesis from support. One of the possibilities of its functional increment is realization of a bouncy characteristic in the knee joint (4). The use of recuperative devices in the articulations and organization of their work by a definite way may partially restore energetic expenditures taking place in consequence of an amputation and thus to contribute to approach the norm of kinematic and dynamic parameters of amputees' gait (5). Using the scheme in Fig.4, let us consider the correlation between joint moments which for the simpliest 3-linked plane model of the lower extremity has the form

$$M_{KI} = M_{ri} + L_r R_i \sin(\alpha_r - \beta) \qquad (I)$$

where M_{KI} ; M_{ri} - respectively are the moments in the knee and ankle articulations;

L_r - a length of a shank;

R_i , β - a value and an angle of inclination of a supporting reaction vector from vertical;

α_r - an angle of inclination of a shank from vertical.

Based on the assumption that use of drives in the knee and ankle joints in combination with rationally selected elastic elements will make it possible to approach the norm kinematic and dynamic parameters of the walking, taking into account the eguation (I) it is possible to write

$$\Delta M_{np} = C_2 (\pi - (\alpha_r + \alpha_8)) - C_1 \varphi_1 - L_r R_H \sin(\alpha_{rH} - \beta)_H \qquad (2)$$

where C_I, C_2 - stiffness of the bumpers respectively in the artificial ankle and knee joints;

α_{rH} - an angle of inclination of a shank from vertical in the norm;

φ_1 - inter-link angle in the artificial ankle joint;

α_δ - an angle of inclination of a hip from vertical;

R_H, β_H - a value end an angle of inclination of a supporting reaction vector from vertical in norm;

$M_{np} = M_{rx} - M_{KX}$; (M_{rx} , M_{KX} - a moment created by a drive in the ankle and knee artificial joints respectively.)

With it:

$$M_{rx} = C_2\left(\pi - (\alpha_r + \alpha_\delta)\right) - C_1\varphi_1 - L_r R_H \sin(\alpha_{rH} - \beta_H) + M_{KX} \quad (3)$$

For a below-knee prosthesis the following relation is suitable

$$C_2\left((\pi - (\alpha_r + \alpha_\delta)\right) + C_1\varphi_1 = M_{rx} + L_r R_H \sin(\alpha_{rH} - \beta_H) \quad (4)$$

If assume that a motorized above-the-knee prosthesis is assembled on the base of a hip prosthesis of universal appointment ПН6-35 with a knee unit I6ВД where a bouncy function is not realized then it is possible to write:

$$M_{rx} = C_1\varphi_1 - L_r R_H \sin(\alpha_{rH} - \beta_H) \quad (5)$$

Use of a knee unit provided springed bending at the stance phase by a prosthetic limb (6) as well as the use of the other constructive version results in a considerable change of a control moment in the artificial ankle joint

$$M_{rx} = C_2\left(\pi - (\alpha_r + \alpha_\delta)\right) - C_1\varphi_1 - L_r R_H \sin(\alpha_{rH} - \beta_H) \quad (6)$$

For determination of the moments M_{rx} and M_{KX} let us determine the laws of in time change of the values of stiffness in the ankle C_T (t/T) and in the knee C_2 (t/T) articulations which provide a partial normalization of the walking. For this purpose - let us use the expressions approximating the laws of the change of angles and moments in the knee and ankle. Approximating with a help of a computer the laws of change of angles and moments in the knee end ankle articulations we shall obtain the law of change of a knee angle described by a polynomial of the 9th degree. The IOth degree of the polinomial provides the least mistake while approximating by the polynomial of the law of change of a moment in the knee joint and an angle in the ankle joint in the first approaching; for approximation of the law of change of a moment in the ankle joint a polynomial of the 8th degree is used (Fig.5)

With it :

$$C_1\left(\frac{t}{T}\right)=\frac{M_r}{\varphi_1\left(\frac{t}{T}\right)}=\frac{-11.8+13.6\frac{t}{T}-2.56\left(\frac{t}{T}\right)^2+0.2\left(\frac{t}{T}\right)^3-8.3\cdot10^{-1}\left(\frac{t}{T}\right)^4+1.84\cdot10^{-4}\left(\frac{t}{T}\right)^5-}{7.42-10.85\frac{t}{T}+1.93\left(\frac{t}{T}\right)^2-1.44\cdot10^{-1}\left(\frac{t}{T}\right)^3+5.4\cdot10^{-3}\left(\frac{t}{T}\right)^4-10^{-4}\left(\frac{t}{T}\right)^5+}$$

$$\frac{-2.24\cdot10^{-6}\left(\frac{t}{T}\right)^6+1.4\cdot10^{-8}\left(\frac{t}{T}\right)^7-3.56\cdot10^{-11}\left(\frac{t}{T}\right)^8}{+5.4\cdot10^{-7}\left(\frac{t}{T}\right)^6+1.06\cdot10^{-8}\left(\frac{t}{T}\right)^7-2\cdot10^{-10}\left(\frac{t}{T}\right)^8+1.38\cdot10^{-12}\left(\frac{t}{T}\right)^9-3.39\cdot10^{-15}\left(\frac{t}{T}\right)^{10}}$$

$$C_2\left(\frac{t}{T}\right)=\frac{M_K}{\varphi_2\left(\frac{t}{T}\right)}=\frac{-2.09-1.46\cdot10^{-1}\frac{t}{T}+1.68\left(\frac{t}{T}\right)^2-1.3\cdot10^{-1}\left(\frac{t}{T}\right)^3+3.6\cdot10^{-3}\left(\frac{t}{T}\right)^4-}{5.88\cdot10^{-1}-2.68\frac{t}{T}-9.27\cdot10^{-2}\left(\frac{t}{T}\right)^2+3.04\cdot10^{-2}\left(\frac{t}{T}\right)^3-1.98\cdot10^{-3}\left(\frac{t}{T}\right)^4+}$$

$$\frac{-2.35\cdot10^{-5}\left(\frac{t}{T}\right)^5-5.8\cdot10^{-7}\left(\frac{t}{T}\right)^6+1.09\cdot10^{-8}\left(\frac{t}{T}\right)^7-4.9\cdot10^{-11}\left(\frac{t}{T}\right)^8-1.4\cdot10^{-13}\left(\frac{t}{T}\right)^9+1.2\cdot10^{-15}\left(\frac{t}{T}\right)^{10}}{+6.75\cdot10^{-5}\left(\frac{t}{T}\right)^5-1.3\cdot10^{-6}\left(\frac{t}{T}\right)^6+1.5\cdot10^{-8}\left(\frac{t}{T}\right)^7-9\cdot10^{-11}\left(\frac{t}{T}\right)^8+2.19\cdot10^{-13}\left(\frac{t}{T}\right)^9} \quad (7)$$

where $M_r = M_r\left(\frac{t}{T}\right)$, $M_K = M_K\left(\frac{t}{T}\right)$ - a moment in the ankle and knee joints in norm (Fig. 6_r, $6_б$).

$\varphi_1\left(\frac{t}{T}\right)$, $\varphi_2\left(\frac{t}{T}\right)$ - dependence of an interlink angle in the ankle joint (AJ), Fig.6в, and in the knee joint (KJ), Fig.6a, while human walking in norm (7).

Using the given interrelationships we may obtain the dependence $C_1 = C_1$ (t/T) and $C_2 = C_2$ (t/T), Fig.7. By plotting a graph of the change of the derivatives $\dot{\varphi}_2$ and $\dot{\varphi}_1$ (Fig. 8a and 8в), let us determine on what sections a magnitude of products $\dot{\varphi}_2 M_K$, $\dot{\varphi}_1 M_r$, i.e. powers, is negative (Figs.8б, 8г). Evidently it is possible to provide recuperation of energy in these sections by means of elastic prosthetic elements. The magnitude $\dot{\varphi}_2 M_K$ takes a negative meaning in the sections 4-14%, 50-67% and the magnitude $\dot{\varphi}_2 M_K$ - in the sections 0-7%, 16-45%. Therefore a storage of energy in bumper devices is possible in these sections.

Using the given interrelations we may obtain the dependence $C_1 = C_1$ (φ_1), $C_2 = C_2$ (φ_2), Fig.9,10 in these sections. With a purpose of realization of the dependence obtained let us determine an averaged stiffness of a hind part of the foot as

$$C_{SO} = \frac{\int_{\varphi_A}^{\varphi_B} C_1(\varphi_1)\,d\varphi}{|\varphi_B-\varphi_A|} \quad (8)$$

where φ_A , φ_B - boundery meanings of the angles in the section considered.
By analogous way let us determine a value of stiffness of a fore part of the foot

$$C_{n0} = \frac{\int_0^{\varphi_E} C_1(\varphi_1)d\varphi}{\varphi_E} \qquad (9)$$

As it is evident from correlations obtained (7 - 9) and taking into account (I) a value of stiffness of elastic elements is correlated with anthropomorphic characteristics of an invalid. Using obtained and known correlations between the lengths of the limb segments and the invalid height it is possible to obtain correlations of the stiffness value in the conditioned range of anthropomorphic characteristics of the persons under test. In particular, for the invalid of a mass 70 kg and height I.7 m the stiffness values of the artificial foot sections equivalent to normal values and obtained with a help of a proposed algorithm, comprise I8.9 $\frac{Nm}{rad}$ (0.33 $\frac{Nm}{degree}$) for a hind part of the foot and I20.3 $\frac{Nm}{rad}$ (2.I $\frac{Nm}{degree}$) - for a fore part of the foot. Fig.7 shows the results of calculation of elastic elements of the knee articulation.

In particular, based on the given dependence for the invalid of a mass 70 kg and height I.7m, the stiffness of the bumper may be permanent value at the knee articulation at an average gait rate untill finishing exit from the state of springed bending (until finishing foot-flat stance - 40-43% of a stride time) and comprises C_2^{I} = 9I.6 $\frac{Nm}{rad}$ (I.6 $\frac{Nm}{degree}$).
During flexion in the artificial knee joint the stiffness value is equal C_2 = 40.I $\frac{Nm}{rad}$ (0.7 $\frac{Nm}{degree}$). If we know the values $C_{3.0}$, C_{n0}, C_2^{I} and C_2^{II}, let us determine the values of the moments $C_{3.0} \cdot \varphi_1$, $C_{n0} \cdot \varphi_1$, $C_2^{I} \cdot \varphi_2$, $C_2^{II} \cdot \varphi_2$ in the sections where C_I and C_2 take negative meanings (Fig.7)
Then, based on the expression (3) let us determine the law of the change of a moment exerted by a drive in the ankle-joint (AJ) in time for the lower limb prosthesis with an external source of energy which is shown in Fig.II. The maximal value of a moment is equal 84Nm when a knee unit I6АЛ is used (Fig.IIa). The maximal value of a moment is equal 72 Nm for the case when the stiffness of the bumpers in the artificial knee joint (KJ) during springed bending comprises a permanent value C_2^{I} (till finishing foot-flat stance - 40-43 % of a stride time); then, during flexion , the stiffness of the bumpers is equal to another permanent value C_2^{II} (Fig.IIб) and the maximal value of a moment for the below-knee prosthesis is equal 48 Nm (Fig.8a).

By plotting the dependence of a moment exerted by the drive in the ankle joint (AJ) on the value of an inter-link angle in the AJ let us determine the efficiency of the bumpers application.

Thus, the value of work which must be done by the drive in the AJ at the toe-off period at turnabout of an artificial foot for the angle value changing in the limits from a maximal angle value of dorsal flexion till maximal angle value of plantar flexion (Fig.I2a), is equal 32J. The value of the drive work in the case of a hip prosthesis with a bouncy function and a bumper mechanism in the knee joint (KJ), with possibility of change of hip stiffness from the value $C_2^{I} = 91.6\ \frac{Nm}{rad}$ ($1.6\frac{Nm}{degree}$) while springed bending to the value $C_2^{II} = 40.1\ \frac{Nm}{rad}$ ($0.7\frac{Nm}{degree}$) while flexion is equal 22.5 J. If take the energy consumption and required power of a prosthetic drive not using elastic elements for 100%, then in the case considered the required power of the drive can be decreased by 35%. In case of a below-knee prosthesis the work of a drive is equal 18.8 J, the work being determined as

$$A = \mathcal{M}_M \cdot \mathcal{M}_\varphi \cdot S$$

where $\mathcal{M}_M$ - a scale coefficient of a moment;

$\mathcal{M}_\varphi$ - a scale coefficient of an inter_ - link angle;

S - an area limited by an abscissa axis and a curve of change of an appropriate moment.

Introduction of a bouncy function into the lower limb prosthesis with an external source of energy as well as of rationally selected recuperators is an important foundation for creation of a lightened small-sized drive.

Conclusions

I. Consideration of problems of prosthesis building from the standpoint of a theory of biotechnical systems makes it possible to study connections and regularities taking place in a system " man-prosthesis" most full and comprehensively.

2. Realization of a bouncy function in the hip prosthesis with an external source of energy is one of prospective directions on decreasing asymmetry of locomotions and optimal selection of the principal characteristics of the system. In particular, during walking on the above-knee prosthesis with an external source of energy, with a springed bending and elastic elements, required power of the drive in the artificial ankle joint can be reduced by 35% in comparison with the walking on the motorized above-knee prosthesis without bouncy function.

3. The law of control of the drive of above-knee prosthesis with an external source of energy has been obtained - the law of a moment in the artificial ankle joint.

4. Use of a graphoanalytical method in modelling of biomechanics of the walking, in particular, in control of movement is a rather convinient and relatively simple method.

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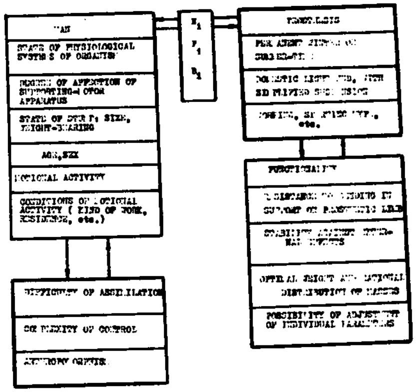


Fig.I The main elements of BTS " Man-Prosthesis"; N_i, F_i, B_i respectively: indicators of prescription, functionality, reliability.

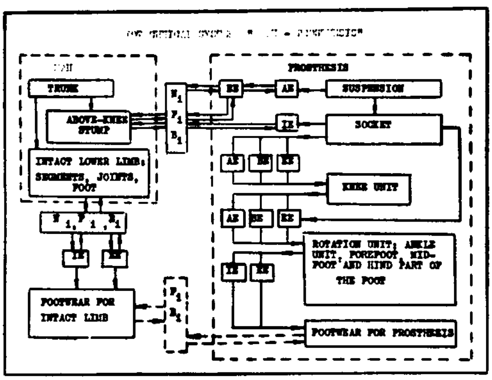


Fig.2 Structural diagram of BTS " Man-Prosthesis" in case of above-knee amputation; EE,AE,IE,BE - respectively: elastic, adjustment, intermediate and bearing elements.

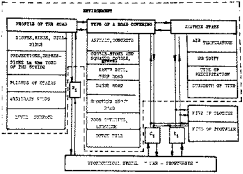


Fig.3 Types of external relations of BTS "Man-Prosthesis" in real conditions **of** functioning; C_i - indicators of relationship of a propelling agent with a road covering; K_i - indicators of control reliability **of a PL (prosthetic limb)**

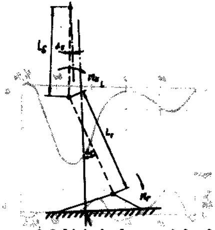


Fig.4 Scheme of 3-linked plane model of a lower extremity.

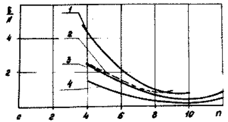


Fig.5 A graph of dependence of a ratio of an approximation error to the number of experimental points δ/N on the degree of a polynominal n

1 - for the dependence φ_2 / $\frac{t}{T}$ /

2 - for the dependence M_r / $\frac{t}{T}$ /

3 - for the dependence φ_1 / $\frac{t}{T}$ /

4 - for the dependence M_K / $\frac{t}{T}$ /

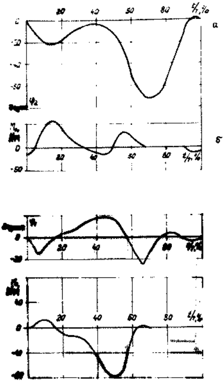
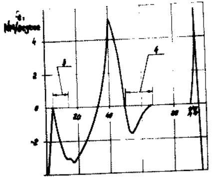


Fig.6 A graph of dependence on the time of **a stride.**
a-of an inter-linked angle in the KJ
δ-of a moment in the KJ
б-of an inter-linked angle **in the AJ**
г-of a moment in the AJ



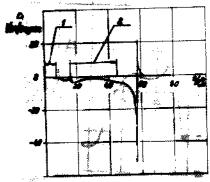


Fig.7. a - a **graph of** dependence of the **stiffness** value at the ankle articulation **on the value of** an inter-linked angle
I - a section of $C_{3.0}$ selection
2 - a section of $C^{3.0}_{II.0}$ selection

б - a graph of dependence of the stiffness **value at** the knee articulation **on the** value of an inter-linked angle
3 - a section of $C_2 I$ selection
4 - a section of $C_2^2 II$ selection

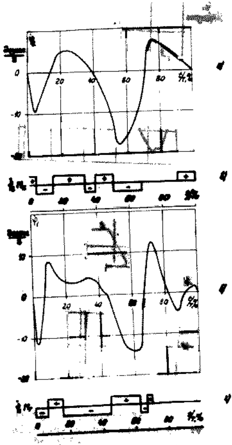


Fig.8 Dependence of a derivative value of an inter-linked angle on the time of a stride.

a - φ_2 φ_1

б -change of the sign ,which takes the magnitude of the product $\varphi_2 \cdot M_K \cdot$

в -change of the sign,which takes the magnitude of the product $\varphi_1 \cdot M_r \cdot$

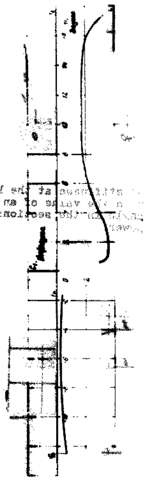


Fig.5 Dependence of stiffness at the ankle articulation on the value of an inter-linked angle in the sections of a negative power.

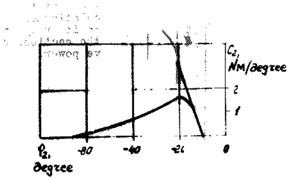


Fig.10 Dependence of stiffness at the knee articulation on the value of an inter-linked angle in the sections of a negative power.

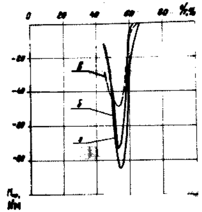


Fig.11 The law of the change of a drive moment in dependence on the time of a stride.
а- while using the knee unit 16 ПЛ
б- if the bumpers stiffness in the KJ is equal to a permanent value C_1^{I} till finishing flat-foot support, and then, during flexion is equal C_2^{II}
в- for the below - knee prostheses.

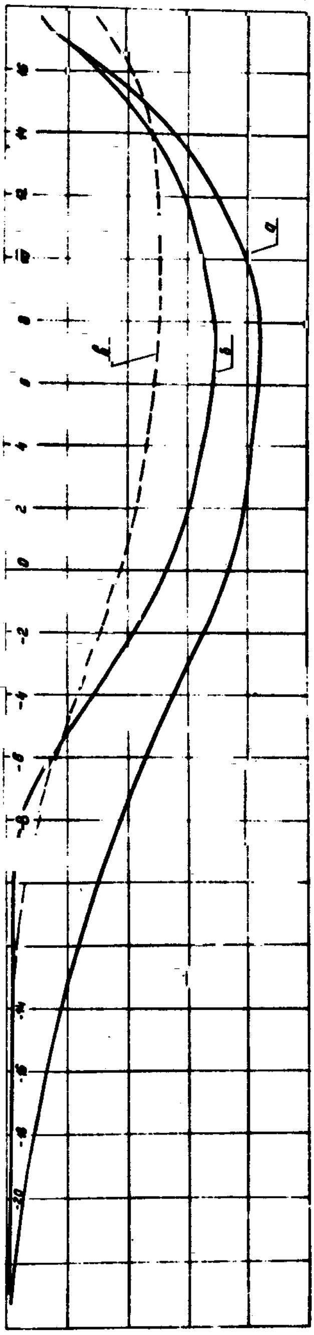


Fig.12 The law of the change of a drive moment in dependence of an inter-linked angle
a- while using the knee unit 16ПЛ
б- if the bumpers stiffness in the KJ is equal to a permanent value C_2^I till finishing flat-foot-support, and then, during flexion is equal C_2^{II}.
в- for the below-knee prosthesis.