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JOINT POSITION CONTROL BY EXTERNAL NERVOUS STIMULATION AND EXTENSION TO HUMAN WALKING

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Summary

In this paper, the results given concern two important points of the rehabilitation problem : 1°) joint motion control by nervous stimulation, 2°) possibilities of extension to the main joints of the human body. The first point is concerned with the modelling and the position control of a single joint by means of pulse width modulation of the signal sent to the agonist muscle nerve. Experiments on numerous dog's ankles prove that the position control is easy (taking precautions about fatigue) and the model parameters are valid with various dogs.

The previous result can be used for several joints if the motions of human body are known. For this, the human body-is considered as an articulated system divided into ten links (including foot flexibility) with 19 degrees of freedom. General equations of the system are found and a linearization is justified for walking. The controllability of the overall system is discussed and the results are compared to those available in the litterature. This allows one to determine realistic conditions, working up the paraplegic walking.

I - Introduction

Functional - Electrical - Stimulation (F. E. S.) is a means of rehabilitating certain handicapped persons. Its study requires two imperative parallel approaches. In the first one, it is necessary to control the motion of a joint with a stimulation signal. In this method one needs to know the open-loop behavior of the neuro-muscular system (1), (2) and of the joint. In order to avoid parasitic oscillations, the non-linearities coming from the muscular contraction process (threshold, saturation, hysteresis) (3), (4) have to be identified as well as those of the joint (mechanical limits, force of friction).

The second approach must determine whether all joints can be simultaneously controlled by F. E. S. as well as the total motion of the human body and if it is possible to suitably reproduce an essential function, such as walking. Although many functional models of walking are known (5), (6), (7), it is necessary to introduce some additional degrees of freedom in order to obtain a harmonious and adaptive motion.

In this paper, these two complementary aspects are studied. First of all, a realistic model of a joint with a single degree of freedom is given. It allows one to control the position of the joint by varying the pulse width of the stimulation. A mathematical model for human walking is then described. From the analysis of its equation, particular properties are found which should facilitate the steps towards the theoretical synthesis of a control system.

II - Model of a joint with a single degree of freedom

II - 1 Motion of the joint

Experiments have been carried out on anterior tibialis and triceps surae muscles of dogs under anaesthesia. The stimulating signal is applied with electrodes on the tibialis or peroneus communis nerve. The rotations of the ankle are measured with a potentiometric transducer. Forces are read with a dynanometric ring to wich are attached four bridge connected metallic stain-gauges. Experimental devices (8) are shown in figure 1.

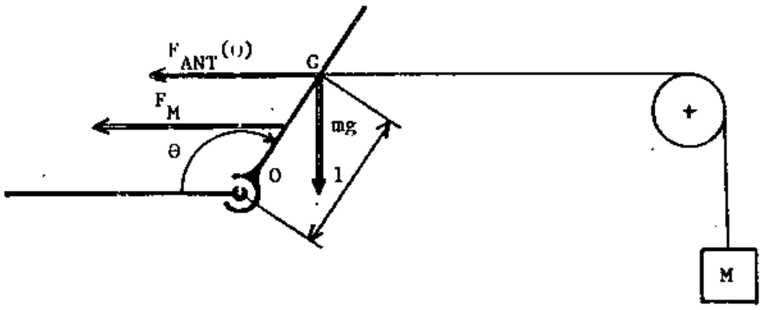

Figure 1 : Experimental devices

Considering the forces applied to the free lever (i.e. the foot), it is easy to write the following differential equation which describes the motion of the joint :

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

$$\dot{\theta} = \frac{d\theta}{dt}$$

* J denotes the moment of inertia of the free lever with respect to the axis of the joint
* θ is the joint position, i.e. the angle determined by the foot axis and the leg axis
* F_M represents the force developed by the stimulated muscular group
* M and m are respectively the external load and the mass of the foot including the position transducer
* a_1 is a gain coefficient, homogeneous to a length
* ξ represents a viscous damping coefficient
* l is the distance from the centre of rotation of the joint to the point where the external load is applied. We assume that this last point is the centre of gravity of the foot.
* F_{ANT} is the force resulting from the passive antagonistic mechanical effects (non-stimulated antagonistic group, joint limits, ligaments) and is applied to the centre of gravity.

II - 2 Characterization of the joint

Equation (1) depends on three variables F_M, F_{ANT} and θ. The position θ is measured during the experiments. F_{ANT} and F_M are more difficult to approach directly. F_{ANT} is a function of the position θ and is first experimentally evaluated. Then, the relation between the modulation voltage (i.e., the stimulating signal) and the developed forces $F_M(t)$ is identified by separation of the muscular agonistic group from the free lever. The total block diagram of the joint is shown in figure 2. It is a non linear closed-loop system. The parameters to be identified are $k_1 = a_1/J$, $k_2 = 1/J$ and $k_3 = \xi/J$. The electro-mechanical part of the model including only the stimulator, the nerve and the muscle is shown in the left of figure 2. The threshold and the saturation have been experimentally found. The time constant τ represents the time necessary to reach the steady state.

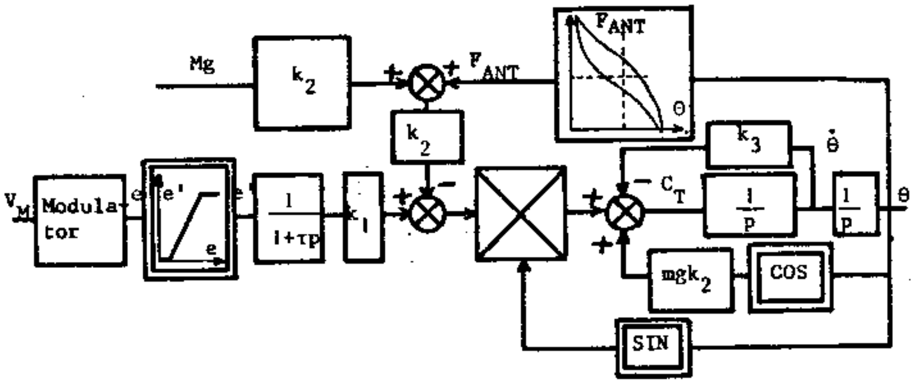

Figure 2 : Total block diagram of the joint

II - 3 Evaluation of the parameters

II - 3 - 1 Electro-mechanical part

The control of the muscular contraction is obtained by nervous stimulation with pulse width modulation. With a pulse frequency of 45 Hz and 150 mV amplitude, the threshold and the saturation have been evaluated respectively as 180 µs and 1 ms. The gain G and the time constant τ have been estimated by a Kalman's linear filter. The results are :

K = 0.65
τ = 0.05 sec.

The time history of K and τ during the estimation process, is shown in figure 3.

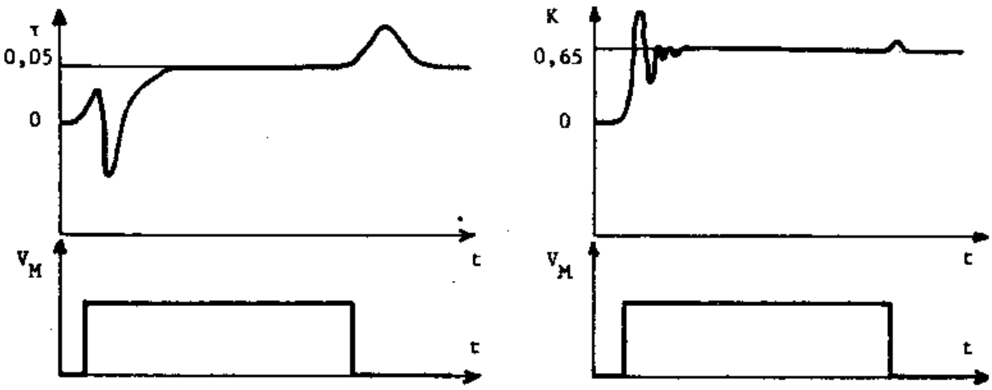

Figure 3 : Time history of K and τ

This proves the convergence of the two parameter values. Figure 4 shows that the actual and simulated outputs are identical when the system input is a step-function.

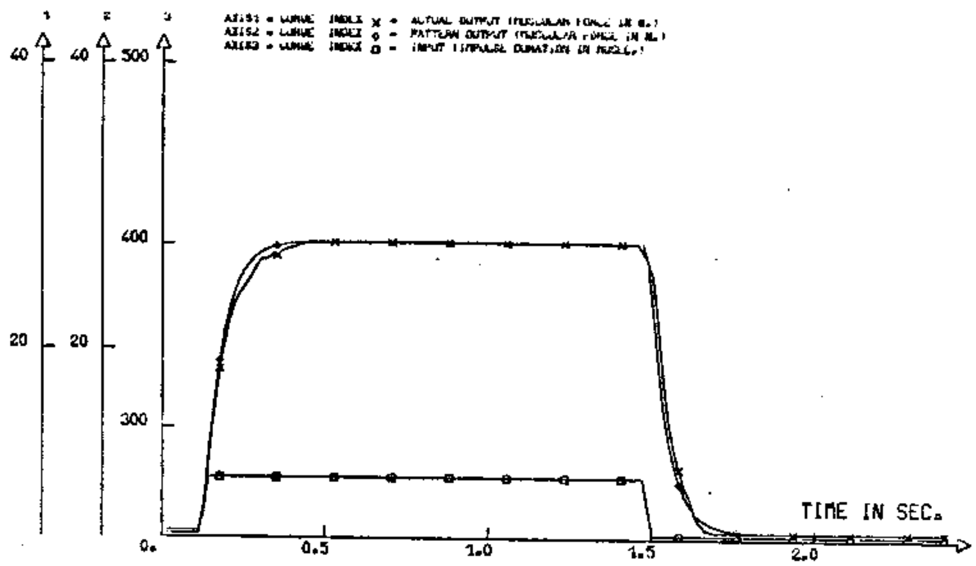

Figure 4 : Simulation of the electro-mechanical model

II - 3 - 2 The complete model

To identify the parameters of the joint, the joint position has been simulated using the output signal F_M of the previous model as the process input (9). The identification has been led through two stages. The first one consists of searching for a point of the parameter space which minimizes the error between the actual and the simulated outputs. The second stage is to define the error areas around this point. We have computed the minimum of E, given by the formula (2) in the parameter space $\{k_1, k_2, k_3\}$.

$$E = 100 \times \frac{\int_H \left(\theta_{MODEL}(t) - \theta_{ACTUAL}(t)\right)^2 dt}{\int_H \left(\theta_{ACTUAL}(t) - \overline{\theta}_{AVERAGE}\right)^2 dt} \qquad (2)$$

Test n° 2-23 and 4-24 are trials offered as examples where the external loads M are 1 kg and 1.5 kg respectively (table 1).

Table 1 :

Test	$k_1 (kg.m)^{-1}$	$k_2 (kg.m)^{-1}$	$k_3 (m.sec.)^{-1}$	E (%)
3-23	34	80	58.5	5.35
4-24	30.5	80	108	4.17

With a relative error criterion E of 10 %, the following error domains are obtained for the same tests (table 2).

Table 2 : Error domains

	Maximum		Minimum		Average	
Test	3-23	4-24	3-23	4-24	3-23	4-24
k_1	65.498	35.461	27.656	25.257	46.577	30.359
k_2	170.960	90.734	72.566	64.388	121.763	77.561
k_3	104.108	124.483	55.248	98.456	79.678	111.469

The best point in the parametric space has been used in the simulation of the joint behavior. When a stepwise width signal is applied to the nerve, the results are those shown in figure 5. By simulation, it is also possible to know the evolution of the total torque applied to the joint and the passive antagonistic effects . The damped oscillations of the position θ when the stimulation is over, are due to mechanical vibrations of the metallic frame.

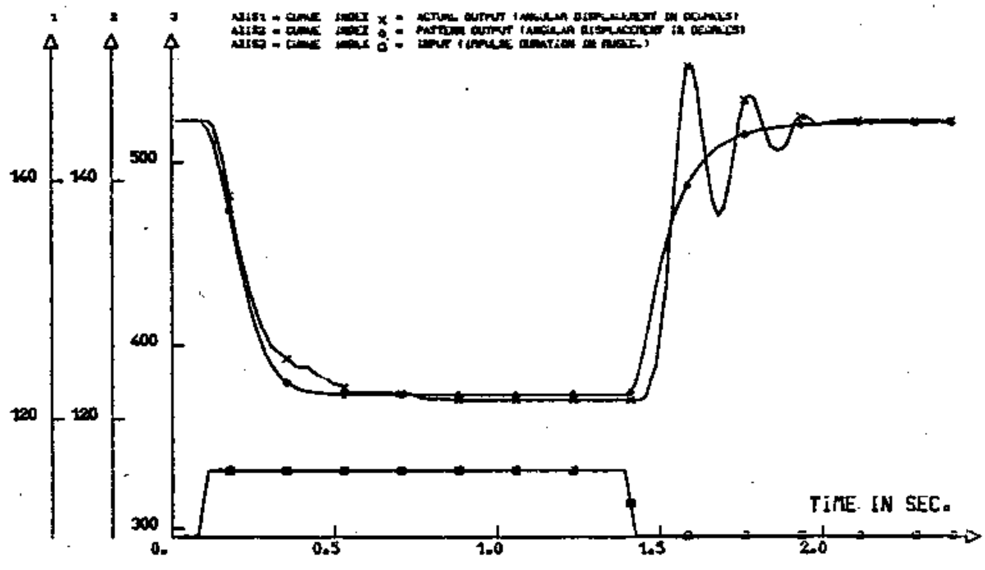

Figure 5 : Simulation of the complete model

II - 4 Advantages and extensions of this identification procedure

The identification method described here presents several advantages :

- It is not necessary to have a good knowledge of the biomechanical data. These data are not generally known with accuracy.
- This model takes into account the non-linear effects met near the limit conditions.
- Although the total number of parameters is small, the model is a good representation of the actual behavior of the joint and of the evolution of internal variables.

This open-loop study of the joint is thus satisfactory and will allow the control of joint position in a closed-loop manner.

If it is possible to extend the previous results to joints with several degrees of freedom, and then, to several joints, human walking might be controlled. However, if is necessary to take into account the coordinations of various individual joint motions and, consequently, to have first a dynamic model of locomotion. Such a model is proposed in the sequel.

III - Mechanical model of the human body during legged-locomotion

Writing equations of human body motions is simplified if the limbs and trunk are assumed to be a set of interconnected undeformable segments. This assumption is justified for the legs and the thighs but is not quite true for the trunk and the feet. Indeed, the distorted structure of the foot plays a prominent part in the propulsive period of the walk. The various segments which represent the skeletal levers are connected by very complex joints ; in the proposed model, we characterize them by rotoïdal or spherical perfect joints. The segments and the degrees of freedom are shown in figure 6.

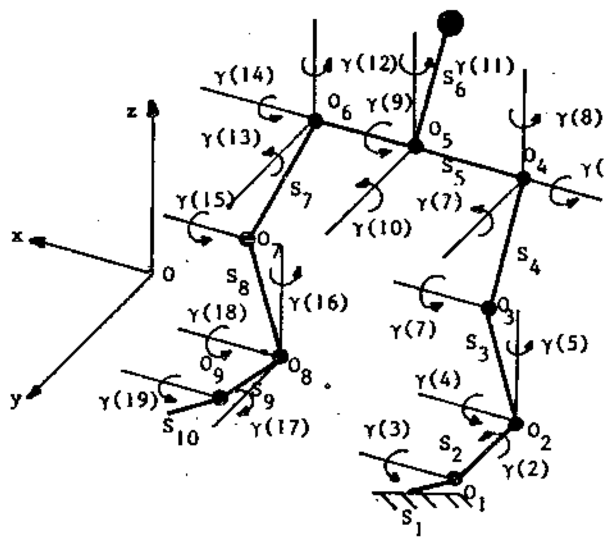

Figure 6 : Description of the mechanical model.

This system forms a polyarticulated unit with ten segments and 19 degrees of freedom. It can be described by Lagrange 's equations :

$$\sum_{j=1}^{N} \left(\frac{d}{dt}\left(\frac{\partial T_j}{\partial \dot{\gamma}_i}\right) - \frac{\partial U_j}{\partial \gamma_i}\right) = \sum_{j=1}^{N} C_j^i \qquad (3)$$

* $N = 10$ denotes the total number of segments
* T_j is the kinetic energy of the segment S_j in the frame Oxyz
* U_j is the potential energy of S_j
* γ_i with $i = 1, 2, \ldots 19$ are the generalized coordinates of the system ; here, the angular displacements are considered as coordinates. This choice allows one to enlarge the range of validity when linearizations are performed.
* C_j^i are the moments of external forces applied to the segment S_j and which are compatible with the rotation γ_i.

III - 1 Computation of the kinetic energy

The variations of the angles γ_i are assumed to be small during the movements. The kinetic energy is a quadratic expression of generalized angular velocities.

$$2T = \sum_{i=1}^{N} 2T_i = \dot{\Gamma}^T . A . \dot{\Gamma} = \sum_{j=1}^{19} \sum_{k=1}^{19} a_{jk} \dot{\gamma}_j \dot{\gamma}_k \qquad (4)$$

$$2T_i = \Omega^T(S_i/R) . \underline{\underline{J}}(G_i, S_i) . \Omega(S_i/R) + M_i(V(G_i/R))^2 \qquad (5)$$

In (4) and (5) :

* $\dot{\Gamma}^T = (\dot{\gamma}_1, \dot{\gamma}_2, \ldots, \dot{\gamma}_{19})$ is the vector of generalized velocities
* $A = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ a_{21} & & \\ \vdots & & \\ a_{n1} & & a_{nn} \end{pmatrix}$ is a symmetric matrix (constant after linearization). Here, $n = 19$
* $\Omega(S_i/R)$ is the rotation vector of the solid S_i in the fixed frame Oxyz
* $\underline{\underline{J}}(G_i, S_i)$ is the tensor of inertia of S_i applied to its centre of gravity G_i, in the main frame of inertia
* $V(G_i/R)$ is the velocity vector of G_i with respect to the fixed frame Oxyz.

In a first approximation, the centres of gravity of the segments are assumed to lie on the axis, linking two consecutive joints. This assumption allows one to characterize the segment S_i with the following parameters :

* m_i mass of segment S_i
* d_i distance from joint S_{i-1}/S_i to the centre of gravity of segment S_i
* l_i distance from joint S_{i-1}/S_i to joint S_i/S_{i+1}
* $\underline{\underline{J}}(G_i, S_i)$ central tensor of inertia of S_i. The terms J_x^i, J_y^i and J_z^i are the only ones not equal to zero.

Having thus obtained the expression of the kinetic energy, partial derivation with respect to $\dot{\gamma}_i$ and derivation with respect to time give :

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{\gamma}_i}\right) = A\ddot{\Gamma} \qquad (6)$$

$\ddot{\Gamma} = (\ddot{\gamma}_1, \ddot{\gamma}_2, \ldots, \ddot{\gamma}_{19})^T$ is the vector of generalized accelerations.

III - 2 Computation of the potential energy

The previous assumptions are still valid. The position z_i of the centres of gravity of the various segments must be computed as a function of the generalized coordinates γ_i. The potential energy is :

$$U = g \sum_{i=1}^{N} m_i z_i , \quad g = 9{,}81 \ m/s^2 \qquad (7) \quad \text{from which :}$$

$$\frac{\partial U}{\partial \gamma_j} = g \sum_{i=1}^{N} m_i \frac{\partial z_i}{\partial \gamma_j} = g \sum_{i=1}^{N} m_i \sum_{k=1}^{19} b'_{ik} \gamma_k \qquad (8)$$

In the non-linear general case, these expressions have been analytically computed with a view to their use for simulations. However, in order to facilitate the analysis of the system properties and the synthesis of the control laws, the linear terms $\frac{\partial U}{\partial \gamma_i}$ are given as a function of coordinates γ_k. It is necessary to obtain the development of z_i up to the second power with respect to the variables γ_k. So, the matric equation is :

$\frac{\partial U}{\partial \Gamma} = B\Gamma + C$ where :

* Γ is the vector of the generalized coordinates
* B is the constant symmetric matrix of the gravity forces
* C is a constant vector.

At this stage, it is possible to eventually take into account unlevel ground on which walking takes place, by introducing two additional variables α_o and β_o which characterize, for each half step, the horizontal components of the unit vector of the normal to the contact surface between the foot and the ground.

Denoting by D the vector of external torques which represent dissipative forces, disturbances and the active torques, the matric expression for Lagrange's equations is put under the form :

$$A\ddot{\Gamma} - B\Gamma - C = D$$

The matric differential equation which describes the behavior of the total system can be written :

$$\ddot{\Gamma} = (A^{-1}B) \cdot \Gamma + A^{-1}(C + D) \qquad (9)$$

(A is a non singular matrix because the quadratic form T is strictly positive-definiteness).

The linearization allows one to obtain the matric equation with constant coefficients. The descriptive studies of walking show that this linearization is valid although the total displacements may be large.

III - 3 Analysis of the matric equation (9)

Equation (9) is useful if it is possible to find out easily the influence of a control vector on locomotion. So, let us write (9) in the classical form of matric equations of the automatic control theory :

$$\dot{X} = FX + Ru \qquad (10)$$

$$\text{with : } \begin{cases} u = (C + D) ; R^T = (0 \mid A^{-1}) ; F = \left(\begin{array}{c|c} 0 & I \\ \hline A^{-1}B & 0 \end{array}\right) \\ X^T = (\gamma_1, \gamma_2, \dots, \gamma_{19}, \dot{\gamma}_1, \dot{\gamma}_2, \dots, \dot{\gamma}_{19}) \end{cases}$$

$$\text{and : } Y = SX \qquad (11)$$

in which : $Y^T = (y_1 \dots y_1)$ is the output vector. F has remarkable properties :

1°) Its 38 eigenvalues are the square-roots of the 19 eigenvalues of matrix $A^{-1}B$

2°) The modal matrix of F can be built from the eigenvectors of matrix $A^{-1}B$

3°) The matrix $A^{-1}B$ is similar to a symmetric matrix Q built up from the matrix B, the modal matrix of $A^{-1}B$ and the spectral matrix of $A^{-1}B$.

These properties allow us to use the classical iterative Jacobi's method to compute the eigenvalues and the eigenvectors of the matrix F. Diagonalization of F facilitates the analysis of observability and controllability of the proposed system. It is then possible to find out the relative influence of any control vector on each individual mode and on the relative motion of each joint.

IV - Conclusion

The ability to control a joint with a single degree of freedom has been proved. Among other problems, we must discover if the nerves acting on the main joints concerned in the walking process have effects either on a single joint only or on several joints.

Evolution of the locomotion model compared with descriptive data of the litterature shows that the number of degrees of freedom is sufficient. New useful elements are the division of the foot into two parts and the coupling of horizontal motion and that in other planes.

The interesting mathematical properties of this last model lead us to think that this model is realistic and workable for all orthotic devices.

REFERENCES

(1) Caspi, P., Pouliquen, R. and Richalet, J. , "Le muscle strié est-il un générateur de force ou de raideur ; étirements forcés : modèle mathématique", Journal de Physiologie, pp. 345-359, 1970.

(2) Stanič, U. and Trnkoczy, A., "Closed-loop positioning of hemiplegic patient's joint by means of functional electrical stimulation", IEEE Transaction on Biomedical Engineering, pp. 365-370, Sept., 1974.

(3) Gugić, P., Trnkoczy, A. and Stanič, U. , "Hybrid control of the ankle joint", Proceedings of the Fourth International Symposium on External Control of Human Extremities, pp. 617-631, Dubrovnik, Aug., 1972.

(4) Lestienne, F. , "Programme moteur et mécanisme de l'arrêt d'un mouvement monoarticulaire", Thèse d'Etat, Lille, Dec., 1972.

(5) Gubina, F., Hemami, H. and Mc Ghee, R. , "On the dynamic of biped locomotion", IEEE Transaction on Biomedical Engineering, pp. 102-108, March, 1972.

(6) Vukobratovič, M. and Stepanenko, Y. , "Mathematical models of general anthropomorphic systems", Mathematical Biosciences, Vol 17, 1973.

(7) Kato, I., Matsushita, S., and Kato, K. , "A model of human posture control system", Proceedings of the Third International Symposium on External Control of Human Extremities, pp. 443-464, Dubrovnik, Aug., 1969.

(8) Dombre, E., Fournier, A., Coiffet, P. and Peruchon, E. , "Experimental study of muscular response under electrical nervous stimulation", The Fifth International Symposium on External Control of Human Extremities, Dubrovnik, Aug., 1975.

(9) Richalet, J., Rault, A. and Pouliquen, R. , "Identification des processus par la méthode du modèle", Editions Gordon and Breach, 1971.

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(2) Stanič, U. and Trnkoczy, A., "Closed-loop positioning of hemiplegic patient's joint by means of functional electrical stimulation", IEEE Transaction on Biomedical Engineering, pp. 365-370, Sept., 1974.

(3) Gugić, P., Trnkoczy, A. and Stanič, U. , "Hybrid control of the ankle joint", Proceedings of the Fourth International Symposium on External Control of Human Extremities, pp. 617-631, Dubrovnik, Aug., 1972.

(4) Lestienne, F. , "Programme moteur et mécanisme de l'arrêt d'un mouvement monoarticulaire", Thèse d'Etat, Lille, Dec., 1972.

(5) Gubina, F., Hemami, H. and Mc Ghee, R. , "On the dynamic of biped locomotion", IEEE Transaction on Biomedical Engineering, pp. 102-108, March, 1972.

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