Development of active anthropomorphic exoskeletons*

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Abstract—*The basic postulates of this new approach to the study of anthropomorphic systems dynamics are given in the paper. In comparison with other attempts, this approach enables the maximal reduction of dimensionality, being based on prescribing synergy, to one part of the system. As an illustration of the method, an example is given of a complete synergy synthesis for the adopted configuration of the anthropomorphic systems.*

Keywords—*Anthromorphic systems, exoskeletons, rehabilitation, paraplegia, exoskeleton, robots*

Introduction

THE HUMAN SKELETON can be treated as a complex nonlinear multivariable system. To provide complete skeletal activity the human has over 600 muscles available, which represents more than 300 equivalent actuators of bilateral action†. In terms of the mechanical scheme, the system of skeletal activity has over 300 degrees of freedom available. When it is intended to make an artificial model of a locomotion-manipulative two-legged machine the problem arises as to how to reduce the high dimensionality at the dynamic actuator level. Several attempts have been made to reduce the dimensionality of the natural locomotion-manipulative system when synthetising a system using artificial skeletal activity.

TOMOVIĆ and BELLMAN (1970) reduced the skeletal activity to a very limited number of movements using stimulation of the natural locomotor system. This is considered to be a modest project, since not enough is known about the co-ordination of movements during artificial locomotor stimulation (VODOVNIK *et al.*, 1967; 1968).

†*The major part of the muscular system is organised in the form of muscle pairs*

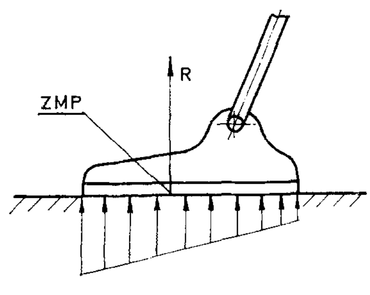


Fig. 1 Zero-moment point (z.m.p.)

* *First received 20th November 1972 and in final form 26th January 1973*

In another approach the dynamics of legged motion is studied; it is treated as a rigid body with six degrees of freedom defined by equations with a discontinuous right-hand side, describing the continuous motion of the body (MCGHEE, 1968; FRANK and MCGHEE, 1969). Discontinuity appears owing

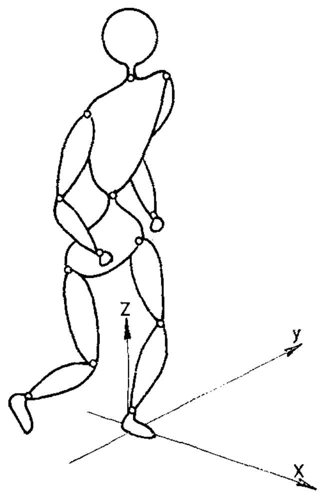


Fig. 2 Joint distribution with biped configuration

to the fact that the forces are generated alternately when the lower extremity contacts the ground. The problem is thus reduced to the calculation of forces and torques generated by the extremities, from which six velocities can be computed; the angles and positions with respect to the stationary system are then obtained by means of integration. This approach involves the use of a mathematical model in the form of classical equations of motion of a rigid body in space under the influence of driving forces and torques. The result is that the system is represented by six degrees of freedom which determine its dimensionality, and thus it is necessary to determine forces and torques by means of appropriate control through feedback for the purpose of generating repeated motion in order to achieve a stable gait. A serious disadvantage of this approach is that massless legs have been adopted. If the masses of the legs were considered, they would cause considerable extensions in the representation of the system model, and the synthesis of the control mechanism would become extremely complex. The addition of each leg introduces at least three additional degrees of freedom, under the conditions of simple joints. To realise the gait algorithm, at least the same number of control signals is necessary. Based on this approach and neglecting the influence of leg masses, an attempt has been made to control the existing degrees of freedom on the basis of the error in the driving torques and forces (Vukobratović *et al.*, 1970). To avoid the limitations of passive stabilisation by which the kinematic gait of the dynamic system, moved by the ' massless ' legs, is basically controlled, a new approach to the study of legged-machine dynamics, particularly for anthropomorphic structures, is described.

Method of prescribed synergy

The basic concept used in the synthesis of artificial synergy is that the law of change for the forces of reaction and friction is given in advance, or their interrelationship has been prescribed. For example, z.m.p.* motion is given, and the points at which the resulting frictional forces act are prescribed. This determination of dynamic values imposes dynamic relations that result in additional dynamic constraints in the system model. Mathematically, this is expressed by additional differential relations that have to be satisfied by the anthropomorphic system motion.

From what has been said, it appears that, if some point represents the z.m.p., and if the vertical ground reaction forces are reduced to it, the moment M should be equal to zero (Fig. 1). The vector M has evidently a horizontal direction, and hence two dynamic conditions have to be satisfied: projections of the moment onto two mutually orthogonal axes in the horizontal plane should be equal to zero. If the fixed horizontal axes are denoted by X and Y,

* *If all elementary reaction forces are reduced to the centre of the support surface, the force* N *and moment* M *are obtained. Since the load diagram of the vertical forces is of the same sign, the ground reaction can always be reduced to the resultant force. This resultan force will be denoted as* R *and its point of action upon the ground surface called the zero-moment point (z.m.p.) (Fig. 1). It is thus assumed that frictional forces can be reduced to the resultant force and moment*

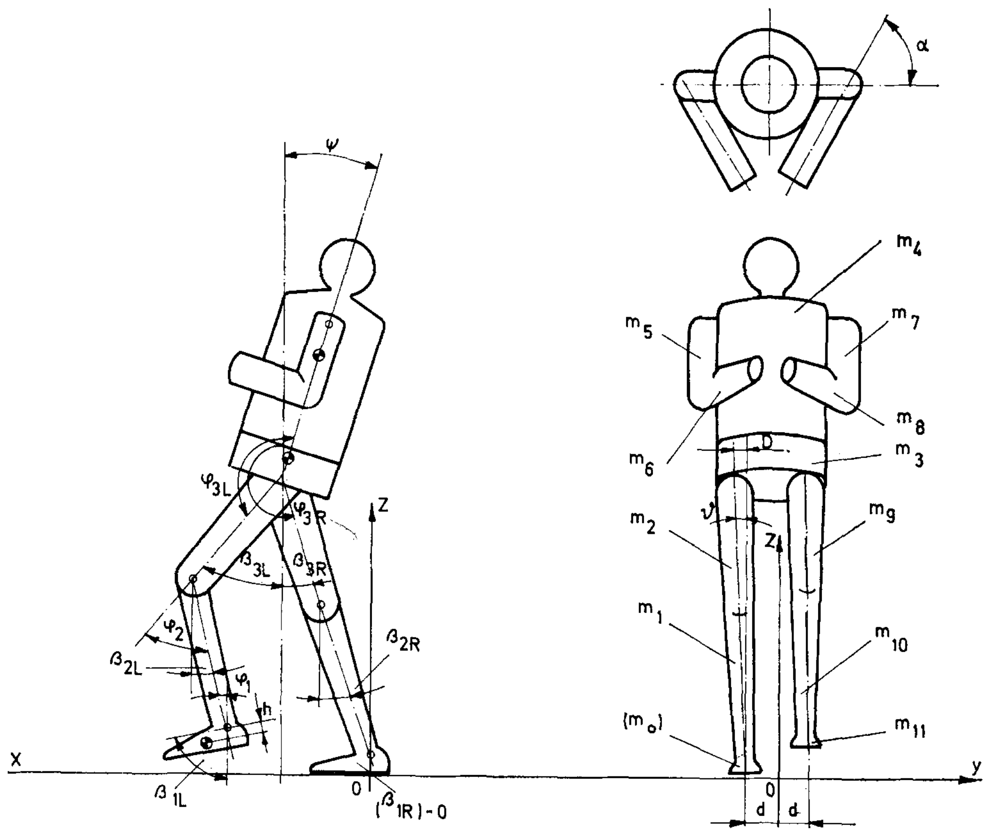


Fig. 3 Mechanical biped model

then

$$\left.\begin{aligned} M_X &= 0 \\ M_Y &= 0 \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (1)$$

With regard to frictional forces, the following condition can be stated: the moment of frictional forces with respect to some vertical axis ζ is equal to zero, and, as a result,

$$M_\zeta = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (2)$$

The axis can pass through the centre of gravity, or the centre of the foot support surface, or through the z.m.p. In the last case, X, Y, ζ constitute an orthogonal co-ordinate system. According to D'Alambert's principle, the system must be in equilibrium. assume that the foot of the anthropomorphic system rests completely on the ground, so that $\phi_0 = 0$. The inertial forces F and moment M_F in the general case can be represented as the linear forms of the generalised accelerations, and as quadratic forms with respect to the generalised velocities:

$$\left.\begin{aligned} \boldsymbol{F} &= \sum_{i=1}^{n} \boldsymbol{a}_i \ddot{\phi}_i + \sum_{i=1}^{n} \sum_{j=1}^{n} \boldsymbol{b}_{ij} \dot{\phi}_i \dot{\phi}_j \\ \boldsymbol{M}_F &= \sum_{i=1}^{n} \boldsymbol{c}_i \ddot{\phi}_i + \sum_{i=1}^{n} \sum_{j=1}^{n} \boldsymbol{d}_{ij} \dot{\phi}_i \dot{\phi}_j \end{aligned}\right\} \quad . \qquad (5)$$

where the vectors $\boldsymbol{a}_i$, $\boldsymbol{b}_{ij}$, $\boldsymbol{c}_i$ and $\boldsymbol{d}_{ij}$ are functions of the generalised co-ordinates.

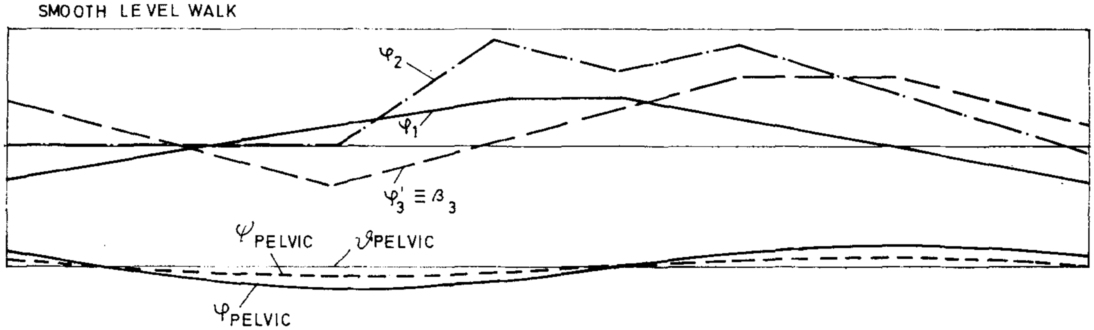


Fig. 4 Gait with negligible pelvic displacements

The external forces acting on the locomotion system include the friction forces, gravity forces and ground reactions. We reduce the moments of these forces and those of the inertial forces to the z.m.p. and denote them by $\boldsymbol{F}$ and $\boldsymbol{M}_F$, respectively. Then, eqn. 1 can be written as

$$\left.\begin{aligned} (\boldsymbol{M}_G + \boldsymbol{M}_F)\,\boldsymbol{e}_x &= 0 \\ (\boldsymbol{M}_G + \boldsymbol{M}_F)\,\boldsymbol{e}_y &= 0 \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (3)$$

where

$\boldsymbol{M}_G$ = total moment of gravity force with respect to the z.m.p.

$\boldsymbol{e}_x, \boldsymbol{e}_y$ = unit vectors of X and Y axes of the fixed co-ordinate system.

The third equation of the dynamic relationships (eqn. 2) can be written as

$$(\boldsymbol{M}_F + \boldsymbol{\rho} \times \boldsymbol{F})\,\boldsymbol{e}_\zeta = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (4)$$

where

$\boldsymbol{\rho}$ = vector from z.m.p. to the ζ axis point of the action on the ground surface

$\boldsymbol{e}_\zeta$ = unit vector of ζ axis.

We denote the generalised co-ordinates of the mechanism* by ϕ_i. In the synergy synthesis we

Introducing these expressions into eqns. 3 and 4, we get

$$\left.\begin{aligned} &\boldsymbol{M}_G \boldsymbol{e}_x + \sum_{i=1}^{n} \boldsymbol{c}_i \boldsymbol{e}_x \ddot{\phi}_i + \sum_{i=1}^{n} \sum_{j=1}^{n} \boldsymbol{d}_{ij} \boldsymbol{e}_x \dot{\phi}_i \dot{\phi}_j = 0 \\ &\boldsymbol{M}_G \boldsymbol{e}_y + \sum_{i=1}^{n} \boldsymbol{c}_i \boldsymbol{e}_y \ddot{\phi}_i + \sum_{i=1}^{n} \sum_{j=1}^{n} \boldsymbol{d}_{ij} \boldsymbol{e}_y \dot{\phi}_i \dot{\phi}_j = 0 \\ &\sum_{i=1}^{n} \boldsymbol{c}_i \boldsymbol{e}_\zeta \ddot{\phi}_i + \sum_{i=1}^{n} \sum_{j=1}^{n} \boldsymbol{d}_{ij} \boldsymbol{e}_\zeta \dot{\phi}_i \dot{\phi}_j \\ &\qquad + \sum_{i=1}^{n} (\boldsymbol{\rho} \times \boldsymbol{a}_i)\,\boldsymbol{e}_\zeta \ddot{\phi}_i \\ &\qquad + \sum_{i=1}^{n} \sum_{j=1}^{n} (\boldsymbol{\rho} \times \boldsymbol{b}_{ij})\,\boldsymbol{e}_\zeta \dot{\phi}_i \dot{\phi}_j = 0 \end{aligned}\right\} \qquad (6)$$

If the locomotion system has three degrees of freedom only, the trajectory of $\phi_i(t)$ for all co-ordinates can be found by integrating eqns. 6. However, the number of degrees of freedom n is generally greater than three; this is obvious because the equilibrium dynamic conditions discussed do not as yet contain any information on the type of the gait.

The laws of the remaining $(n-3)$-co-ordinates change should be set so as to ensure the desired gait; i.e. a periodic displacement of the legs corresponding

* *Generalised co-ordinates ϕ_i of the mechanism represent the system internal co-ordinates.*

to the alternate single- and double-support phases. This information may be obtained at best by directly studying the human gait. In the present state of biomechanics, we can answer the question how a man walks, but it is difficult to say why a particular gait is just like that. Therefore any attempt directly to obtain the laws of change in all the co-ordinates ϕ_i, starting from the minimisation of some global criterion (e.g. minimum power consumption), does not seem to be reasonable.† It seems more reasonable to produce experimentally and record the (Tomović, Vodovnik *et al.*, 1972; 1967). Since the gait algorithm is symmetric, let us write the repeatability conditions for the half-period of the step T, according to Vukobratović and Juričić (1969), as:

$$\phi_i^*(0) = \pm\phi_i^*(T/2);\quad \dot{\phi}_i^*(0) = \pm\dot{\phi}_i^*(T/2) \quad (8)$$

where the + or − sign depends on the physical nature of the appropriate co-ordinates and their derivatives.

The system of eqn. 7, together with the conditions of eqn. 8, make it possible to obtain the necessary

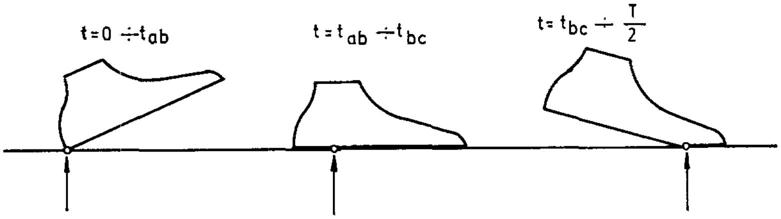


Fig. 5 Zero-moment point displacement during half step.
t_{ab} = time from heel strike to full foot contact
t_{bc} = time from full foot contact to beginning of deploy phase
T = full step period

characteristics of the basic co-ordinates defining the human gait. Evidently, these should be the leg co-ordinates. Thus we have the possibility of obtaining the dynamic laws of change in the $(n-3)$-co-ordinates of the anthropomorphic robots. In this way, the synthesis of artificial synergy is accomplished as follows: for some co-ordinates a fixed program of motion (kinematic algorithm) is set, and the motion of the remaining co-ordinates is found from the dynamic equations (eqns. 6).

Separate the sets of variables ϕ_i into those for which the law of motion has been prescribed and those whose motion has been determined from eqn. 6. Let the first be denoted by $\tilde{\phi}$, and the second by ϕ^*. After the appropriate transformations, the dynamic eqns. 6 can be represented in the matrix form

$$\sum_{i=1}^{n} c_i\ddot{\phi}_i^* + \sum_{i=1}^{n}\sum_{j=1}^{n} d_{ij}\dot{\phi}_i^*\dot{\phi}_j^* + g = 0 \quad . \quad (7)$$

where

c_i, d_{ij} = some vector coefficients depending on $\tilde{\phi}, \dot{\tilde{\phi}}, \phi$.

g = representing function of $\tilde{\phi}$, ϕ^*, $\dot{\tilde{\phi}}$, $\dot{\phi}^*$ co-ordinates.

In accordance with the type of motion of legged living organisms in stationary-gait regimes, certain repeatable conditions, which reflect mathematically the particular feature, have to be added to eqns. 7

† *In the author's opinion, some definite optimisation criteria are only related to particular locomotion activities of the human*

laws of motion of the vector ϕ^*; i.e. to carry out the compensation synergy synthesis. Accordingly, the synergy synthesis for co-ordinates of ϕ^* is reduced to the simultaneous solution of the systems of eqns. 7 and 8. For this purpose, various iterative methods, not considered here, for solving the boundary-value problem can be applied (Vukobratović and Juričić, 1969; Vukobratović *et al.*, 1972).

As already mentioned, it is reasonable to select the co-ordinates $\tilde{\phi}$ as the angular displacements of the robot's 'legs'. This does not mean that they cannot be chosen for other co-ordinates of the model. However, leg motion, in fact, defines the gait, and this motion is more complex than the motion of remaining parts of the anthropomorphic systems. In that case, the co-ordinates ϕ^* refer to the upper part, i.e. the trunk of the robot. In brief, the schematic motion of the robot is as follows: The 'legs' are displaced according to some algorithm recorded from a human being, and the 'trunk' makes periodic compensating movements that provide for appropriate displacement of the z.m.p. and dynamic equilibrium of the system in the frontal, sagittal and horizontal planes.

After the synergy synthesis is completed, it is necessary to compute the driving torques needed for its realisation. For this reason, let us write the conditions of kinetostatic equilibrium around the axes of all the joints (Fig. 2). As a result, we obtain differential equations of the following form:

$$M^k = \sum_{i=1}^{n} c_i^k\ddot{\phi}_i + \sum_{i=1}^{n}\sum_{j=1}^{n} d_i^{\,k}\dot{\phi}_i\dot{\phi}_j + g^k \quad . \quad (9)$$

where the upper index k indicates the joint number in which the chain has been 'broken';

c_i^k, d_{ij}^k, g^k = some vector coefficients

Since the functions $\phi(t)$ from eqn. 9 are known, all the driving torques M_i ($i = 1, 2, \ldots, n$) can be computed. It must be mentioned that, in this short description of the new method, we are concerned with the anthropomorphic model without upper extremities. When the 'free' upper extremities are involved, the model of the dynamic relationships (eqn. 7) is increased by as many second-order differential equations as the 'arms' have degrees of freedom (not discussed here). Since the upper extremities are passive, the driving torques in their corresponding 'free' joints are equal to zero.

Example of the anthropomorphic system synergy synthesis

The basic statements of this approach to the study of anthropomorphic systems dynamics were used for the synthesis of the compensating synergy of the anthropomorphic system illustrated in Fig. 3. The upper part of the structure is represented by a homogeneous rigid body. The lower extremities each possess three degrees of freedom.† The segments of the extremities are interconnected by simple joints. For leg movement (prescribed synergy of the anthropomorphic mechanism), a 'real' gait algorithm was adopted. In Fig. 4, the laws of change in the characteristic angles of the leg are given in the form of diagrams for the case of gait on level ground.‡ The chosen gait type is characterised by very small pelvic movements, because the practical realisation of the walking machine was kept in mind.

According to the algorithm chosen, the foot of the leg in the support phase changes its position from the heel to the toes, as shown in Fig. 5. In this case, we can distinguish three phases. Let us denote by t_{ab} the time instant when the support is transferred from the heel to full foot, and by t_{bc} when it is transferred from the full foot to the toes ($0 < t_{ab} < t_{bc} < T/2$), where T is the full step period.

During the half-period, the z.m.p. changes its position three times in the case considered. At the end of the half-period, z.m.p. shifts under the other foot, which is then in contact with the support. It should be emphasised that such a shift of the support point makes the gait relatively smoother and more natural. However, still greater smoothness of gait and an even more natural aspect could be acquired by adjusting the z.m.p. position to correspond to the double-support phase. This case will not be treated here.

† Here we are concerned with degrees of freedom of the imposed (prescribed) 'leg' algorithm. As already stated, in order to achieve an anthropomorphic gait, a supplementary degree of freedom, to comply with the condition of dynamic equilibrium (angle v in the frontal plane), was given to the lower extremities

‡ The gait on stairs has been elaborated in detail by Vukobratović (1972)

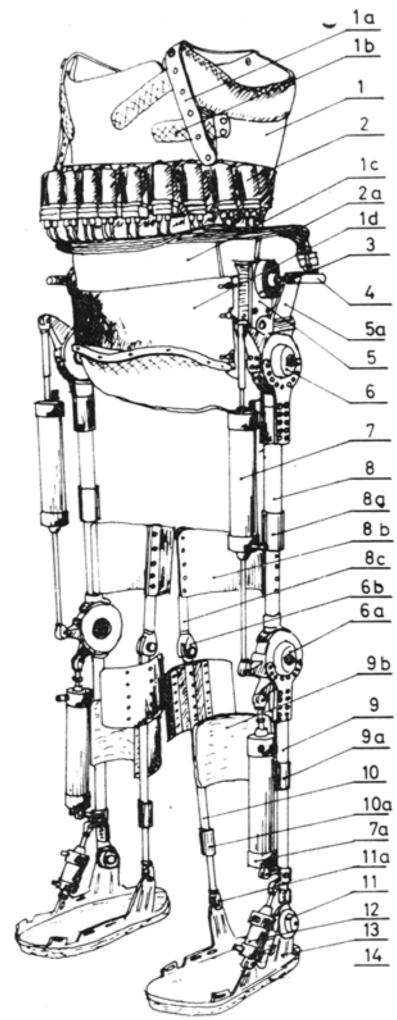


Fig. 6 Complete exoskeleton design

After the type of gait (kinematic algorithm) and z.m.p. positions during contact between the foot and ground (Fig. 5) have been defined, we proceed to the synthesis of the compensating synergy of the upper part of the anthropomorphic system. The characteristic data concerning the geometry and dynamic parameters of the system, shown in Fig. 6, were used as input data for solving this dynamic problem; in fact, this represents the mechanical realisation of the model† shown in Fig. 3. The data on the masses and tensors of inertia are given in

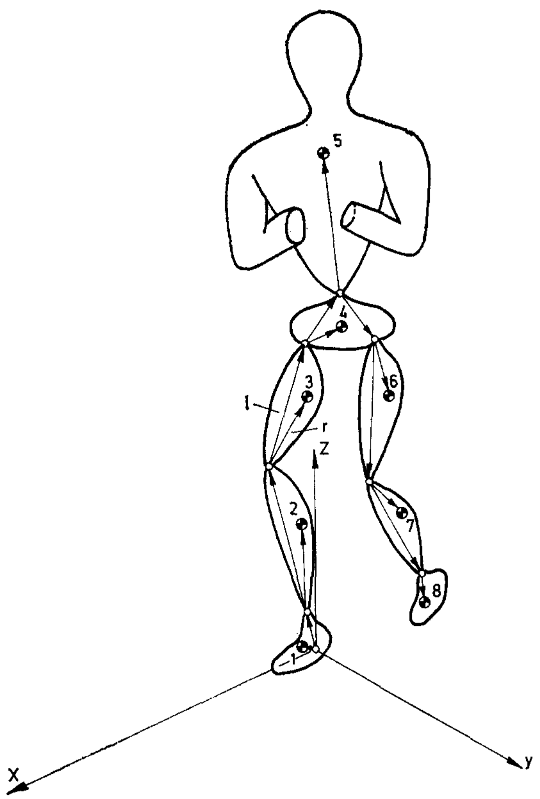
† For practical reasons, the mathematical model was formed according to the configuration given in Fig. 3 (fixed arms). In the realisation of the exoskeleton, the movement of the upper extremities had to be executed according to their calculated synergy. In the opposite case, the 'arms' would represent a perturbation to the system. This necessitates having the arms of the patient fixed in some defined position during the experiment until the conditions for 'arms' movement are established according to the calculated synergy

Table 1. Tables 2 and 3 give the geometrical parameters needed for constructing the mathematical model given in general form by the system of eqns. 6. The meaning of these data can be understood from Fig. 7.

Owing to the chosen type of gait, in which a very small proper pelvic movement is present, and assuming sufficient friction moment with the foot in contact, the synthesis of the compensating synergy was carried out in two planes (sagittal and frontal), which led to the neglect of the third differential equation of the system of eqns. 6.

As a practical result of the synthesis of the upper-part synergy of the anthropomorphic system under consideration, the compensation needed for a repeatable gait of the chosen type* is given in the ψ, υ plane, for the working regime, as follows: $T = 2$ s, $S = 1$ (Fig. 8).

* ψ, ν represent the so-called 'external' co-ordinates of the system differing by a constant from the 'internal' co-ordinates ϕ_i. The reason for adopting 'external' co-ordinates lies in the fact that they are responsible for the system stability, which represents a further step in the realisation of a carefully considered anthropomorphic system capable of operating under perturbed conditions. It should be noted that, in the case of the realisation, the angle ϕ_3 also includes the co-ordinates ψ (Fig. 15)



Development of active exoskeletons

Using this approach, rehabilitation devices of the exoskeleton type have been developed over several years. The first version of this type was realised as the *kinematic walker*. It had one degree of freedom for each leg, and, in agreement with this, one pneumatic actuator (cylinder) each and a pure kinematic link of particular joints. Owing to the need for an upright (standing) position, the gait performed was very similar to the initial gait algorithm on level ground, being defined with two control parameters only† (VUKOBRATOVIĆ and JURIČIĆ, 1969). Using this version, shown in Fig. 10,

† With the first version of the exoskeleton, the 'sliding' gait type defined by one angle (Fig. 9) has been selected

Fig. 7 Anthropomorphic mechanical system with fixed 'arms'

Mass M and moment of inertia‡

m	J_x	J_y	J_z
0·18	0·00007	0·00065	0·00052
0·38	0·0044	0·0044	0·00045
0·98	0·0138	0·0141	0·0035
0·83	0·0079	0·0062	0·0071
4·7	0·211	0·190	0·031
0·98	0·0138	0·0141	0·0035
0·38	0·0044	0·0044	0·00045
0·18	0·00007	0·00065	0·00052

‡ Exoskeleton included weight of patient alone 71 kp

Distance l(m)

i	l_x	l_y	l_z
1	0	0	0·1
2	0	0	0·400
3	0	0	0·45
4	−0·047	0·1	0·09
5	—	—	—
6	0	0	−0·445
7	0	0	−0·400
8	—	—	—

Distance r(m)

i	r_x	r_y	r_z
1	0·030	0	0·038
2	0	0	0·22
3	−0·033	0	0·33
4	−0·034	0·093	0·069
5	0·038	0	0·42
6	−0·032	0	−0·139
7	0	0	−0·192
8	0·030	0	−0·059

the first experiments were performed with two patients at the Orthopaedic Clinic in 1969 and 1970. The results were very modest: the patient 'walked' assisted by two male nurses. Some experience was also acquired about attaching the corselet and the machine itself to the patient's body.

In the course of further work, the model of a *partial active exoskeleton* (Fig. 11) was developed, which made it possible to realise synergy of the legs with three degrees of freedom; while the hip joints had two degrees of freedom and a joint drive in the frontal plane, whereby it was possible also to achieve compensation in that plane (angle υ), which contributed considerably to the realisation of a gait more like that of a human. Clinical tests on this model were performed in 1971 with three patients. The gait of the patients was achieved in a particular go-cart, and more knowledge was acquired of the phenomenon of forces transferred from the machine to the man (and vice versa), local pressures and the like. Constructionally, with the exception of the corselet and the control system, this model is very similar to the latest one:

Complete active exoskeleton—The complete active exoskeleton is intended for the rehabilitation of paraplegics with relatively high lesions, excluding muscular activities of the legs and the waist–pelvic region. In addition to control of the legs, control of the upper part of the body is also possible with this type of exoskeleton. Thus the prescribed gait algorithm is obtained.

The complete exoskeleton (Fig. 12) is made up of three main subassemblies:

corselet with the adjoining subassemblies
left and right 'leg' (Fig. 6).

The corselet 1 was constructed, using standard techniques, of polyester resin reinforced with polyamide fibres. The corselet envelopes the body of the patient from his public–ischiatic region up to the underarms, over the chest and back. It is fastened over the shoulders by means of leather straps (1*a*).

The frontal part (1*c*) of the corselet is a separate unit, which is fastened by Velcro strips (1*b*) to the dorsal part. The ventral portion of the frontal part (cover) (1*d*) is reinforced by a shaped piece of duralumin sheet in order to increase the stiffness of the pelvic part of the corselet. A leather belt (2) containing 14 electropneumatic 3-way valves is fastened to the corselet, and serves to control six pneumatic cylinders (three per leg) as well as two membrane actuators (3), which are pneumatically controlled in parallel and serve as actuators for movements in the frontal plane. Pneumatic pulses are conveyed from the electropneumatic valves to the corresponding actuators via a pneumatic 'cable' formed by polyamide tubes.

The bases (5) of the exoskeleton 'hip' joints are also fastened to the corselet, giving the second degree of freedom to the hip joints (round the longitudinal axis). By means of the lever (5*a*) belonging to the 'leg' subassembly, the drive of the membrane actuators (3) is transmitted to both legs and synchronised by means of a level (4) surrounding the corselet from the rear side in the form of an elongated U. Simultaneously, it drives the linear-feedback potentiometer detecting the position in the frontal plane.

The leg contains three main subassemblies: the 'thigh' with the main hip joint (6), driving an actuator in the form of a pneumatic double-acting cylinder (7), and the adjustable femoral 'bone' (8). The main 'hip' joint is constructed in the form of a simple dry bearing (Teflon sliding surfaces) with adjustable friction. The precision feedback potentiometer is located in the central hole, its 'zero' being adjustable from outside. The elements connecting the base portions of the corselet with the stationary part (cup) of the joint (6) are fastened to the latter, as well as the lever connecting it to the actuator (7). The actuator is manufactured from light alloys, with the exception of the rod, which is made of polished Inox steel. At an air pressure of 10 bar, a net active force of 114 kp is obtained. The femoral 'bone' (8) is manufactured in the form of a 2-member telescopic tube made of Inox steel (wall thickness, 0·8 mm),

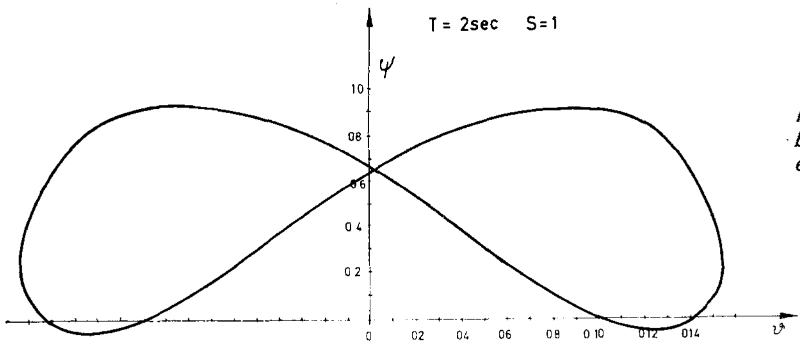


Fig 8 Nominal gait trajectory for biped model with fixed upper extremities
T = step period
S = coefficient of step size

the length of which can be adjusted to the patient by means of a knurled nut (8*a*). The leg support (8*b*) is made of Inox steel sheet and covered with sponge rubber. This part is fastened both to the other part of the femoral 'bone' (8) and to the auxiliary strut (8*c*).

The 'shank' with the main 'knee' joint (6*a*), which is identical to the 'hip' joint (6), also contains the auxiliary joint (6*b*). The actuator (7*a*) is identical to the hip actuator (7). The ,bone' of the 'shank' (9) with the knurled nut (9*a*) is of very similar design to that of the femoral 'bone' (8), while the auxiliary strut (10), with its nut (10*a*), is made of duralumin tubes. The leg support is constructed in the same way as the femoral part of the leg support (8*b*).

The 'foot' of the leg is connected by means of the 'ankle joint' (11) and the auxiliary joint (11*a*) to the 'shank' part of the 'leg'. As well as the other two, the main joint contains a feedback potentiometer. The actuator of the 'foot' (12), is of a design very

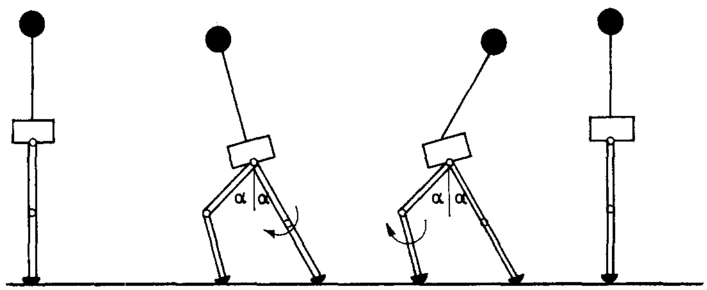


Fig. 9 Simplest biped gait

$$\alpha = \frac{\alpha_m}{2}(1-\cos\omega t)$$

$$\omega = \frac{2\pi}{T}$$

T = half period of the step

similar to that of the actuators (7 and 7*a*). but is of smaller diameter and shorter. The 'foot' (13) itself is made of Inox sheet, stiffened by drawn ribs and swaged edges, and covered on the upper side with expanded plastics sheet. The lower part of the 'foot' (14) is also made of Inox steel sheet and covered on the lower side with semi-hard sponge rubber and fastened to the upper part by means of a longitudinal axle (swivel joint) giving a certain adaptability in the frontal plane. Also, on the lower side of the 'foot' (14), three force transducers with strain gauges are situated, and arranged in such a way as to measure the vertical components of the resultant force at the points of contact of the external and internal balls of the foot and the heel with the ground (Fig. 13). In this way it is possible to monitor continuously the intensity and position of the resultant vertical force component of the system supported on the foot; this has been used in the realisation of the system stabilisation.

Electronic system for complete exoskeleton control

A block schematic of the complete exoskeleton control is given in Fig. 14. The left-leg time-base generator (TBGL) is the synchronisation frequency source. The period T can be regulated within the limits of 1–5 s. The electronic circuit of the right-leg time-base generator (TBGR) is a delay circuit. Output signals from the TBGL and TBGR circuits are related by the expression $VR(t) = VL(t+T/2)$. Fig. 14 shows all seven servosystems for the control of the time changes of the characteristic joint angles ϕ_{1L}, ϕ_{2L}, ϕ_{3L}, ϕ_{1R}, ϕ_{2R}, ϕ_{3R} and υ. Synchronism of the time changes of the angles is preserved by the very fact that all function generators are strictly time connected by the electronic circuits TBGL and TBGR. More precisely, the references of the servosystem are

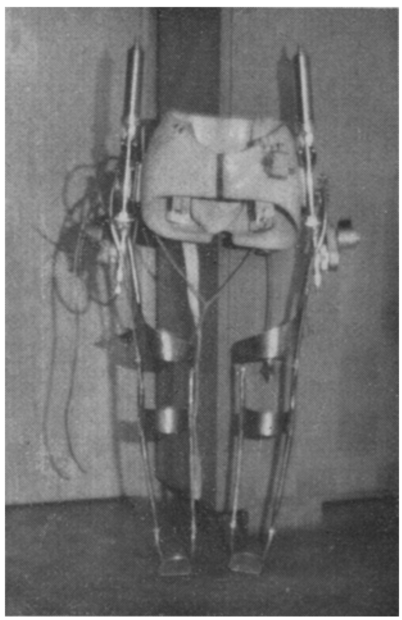


Fig. 10 Kinematic walker (1969)

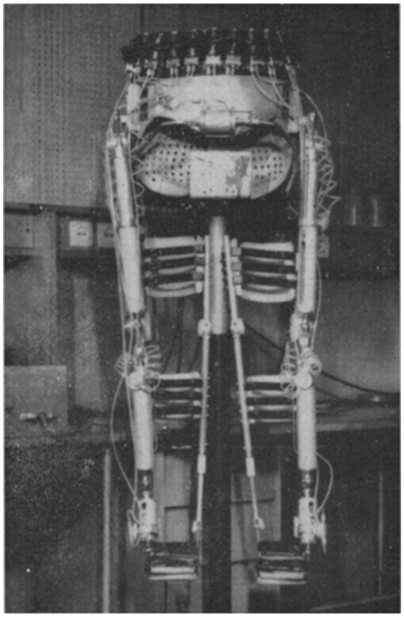


Fig. 11 Partial exoskeleton (1970)

synchronously connected, while the synchronism of the real changes of the angles also depends, apart from the references, on the characteristics of the servosystems.

A description of one servosystem only will be given, since they are all constructed in the same way. A periodic time change of angle ϕ_{1L} with the period T is generated by the circuit Gϕ_1L. The output voltage of the generator is compared with the voltage on potentiometer PL1. The potentiometer is mounted in the ankle joint ϕ_{1L}. After detection and amplification of the error, depending on the error sign, one of circuits PGL or PGU starts to generate pulses. The pulse frequency can be adjusted in advance within the range 10–25 Hz. The pulse width is dependent on the error amplitude. Electromagnetic valves are pulse-powered by circuits PGL and PGU (pulse-generator cylinder lower-end position and pulse-generator cylinder upper-end position, respectively), and they open the air stream towards the upper and lower position, respectively, of the piston of the associated pneumatic cylinder.

Fig. 15 illustrates the electronic realisation of the prescribed (Fig. 4) and the compensating (Fig. 8) synergy in parallel, for comparison. It also shows the realisation of the complete synergy, measured by means of the servo-potentiometer system during the gait of the anthropomorphic system. The measured (realised) synergy is, naturally, expressed in 'internal' angles. For this reason, the electronic realisation of the prescribed program is given in internal co-ordinates, too. For reasons of clarity, Fig. 15 shows a sketch of the system corresponding to the realised structure (Fig. 6). In the same sketch, the necessary designations of angles are given for easier explanation of the realised synergy.

Realisation of global feedback

In the case of perturbations, even when internal synergy $\phi_i(t)$ is strictly fulfilled, the external synergy can be perturbed. For example, the whole system can rotate around the leg in the stance phase in which the 'external' angles β_i, being responsible for gait stability, change. The relation between the external and internal co-ordinates is shown in a simplified sketch of the biped (Fig. 16*a*), for the nonperturbed and perturbed state. This example illustrates how the external synergy can be spoiled even when correctly satisfying the internal synergy. This means, in the general case, that the relationship between the external and internal synergy of the anthropomorphic system can be represented by

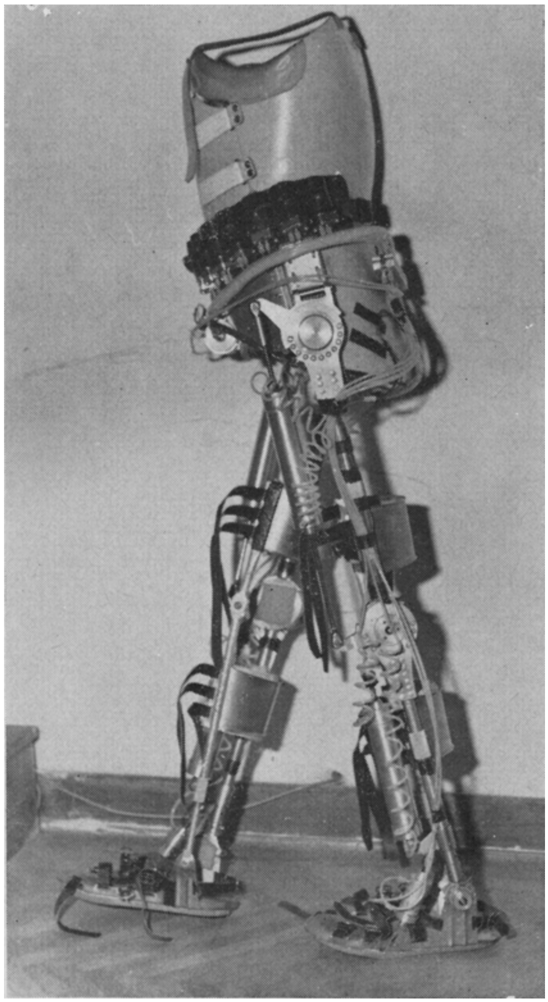


Fig. 12 Complete exoskeleton (1971–72)

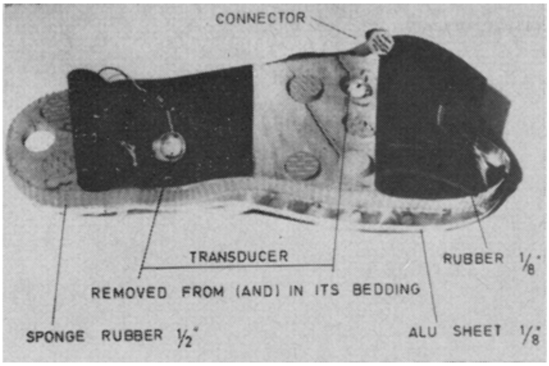


Fig. 13 Artificial foot with force transducers

the matrix equation

$$\beta = B\phi + c \qquad c = \text{constant} \quad . \quad . \quad . \quad . \quad (10)$$

The regulation procedures for stabilisation of the perturbed stationary régimes of the gait will not be dealt with here. They are the subject of another paper by VUKOBRATOVIĆ and STEPANENKO (1972).

We shall briefly describe the regulating scheme based on measuring dynamic reactions during the walk, which avoids the use of gyroscopic instruments.

It is evident that some relationship exists between the force of dynamic reaction $F = (F_X, F_Y, F_Z)$ and the appropriate dynamic moments about three axes connected to the z.m.p.s, $M = (M_X, M_Y, M_Z)$.

Components F_X and F_Y define the moments about the Z axis only. With the previous assumption of a sufficient moment of the frictional forces, we only take into account the component F_Z, which contributes to the appropriate moments round the X and Y axes. We also assume that the 'internal' synergy is realised sufficiently accurately, and that the perturbation only appears in the system external co-ordinates.

Fig. 16*b* illustrates schematically the measurement of the vertical component of the dynamic reaction, from which one can write the following relationships:

$$\left.\begin{aligned} s(F_{BZ} - F_{cZ}) &= M_X \\ d_1\, F_{AZ} - d_2(F_{BZ} + F_{cZ}) &= M_Y \end{aligned}\right\} \quad . \quad . \quad (11)$$

where F_{AZ}, F_{cZ} and F_{cZ} are the vertical components of the reaction, measured at the points A, B and C.

It should be emphasised that, in the nominal regime, the moments M_X and M_Y are by definition equal to zero (z.m.p.). Owing to the perturbed vertical component F_Z, they do, in fact, have values ΔM_X and ΔM_Y. We assume these perturbations to be small.

For the model illustrated in Fig. 3, the components of the moment for z.m.p. can be written as

$$\left.\begin{aligned} M_X &= M_X(\ddot{\psi}, \ddot{\upsilon}, \dot{\psi}, \dot{\upsilon}, \psi, \upsilon, \ddot{\beta}_i, \dot{\beta}_i, \beta_i) \\ M_Y &= M_Y(\ddot{\psi}, \ddot{\upsilon}, \dot{\psi}, \dot{\upsilon}, \psi, \upsilon, \ddot{\beta}_i, \dot{\beta}_i, \beta_i) \end{aligned}\right\} \quad (12)$$

Since the accelerations are the 'most sensitive' factor and a direct consequence of the load change, the increments in moment for the perturbed regime are

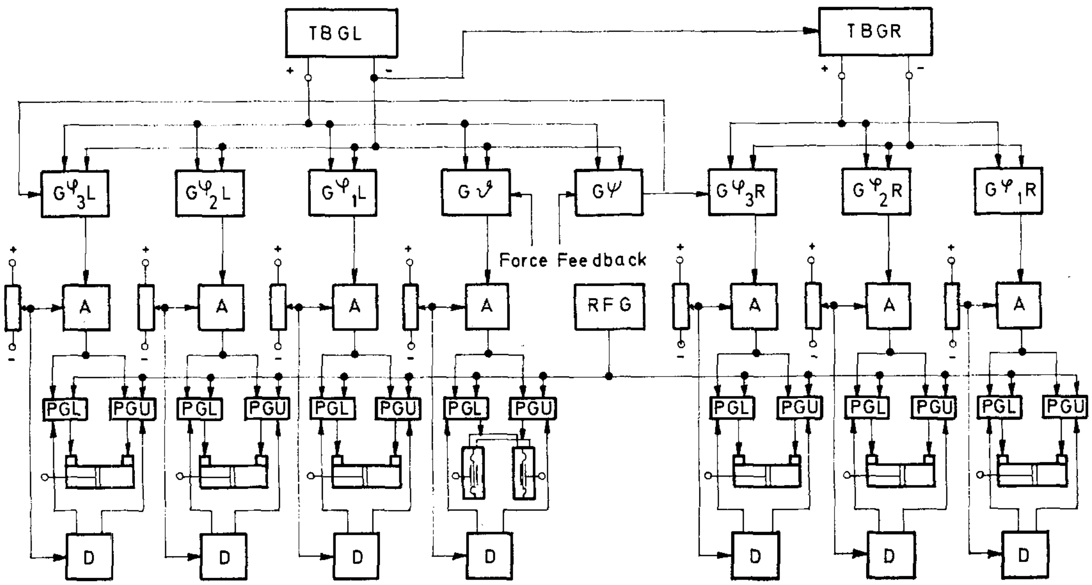


Fig. 14 Block diagram of complete exoskeleton synergy realisation

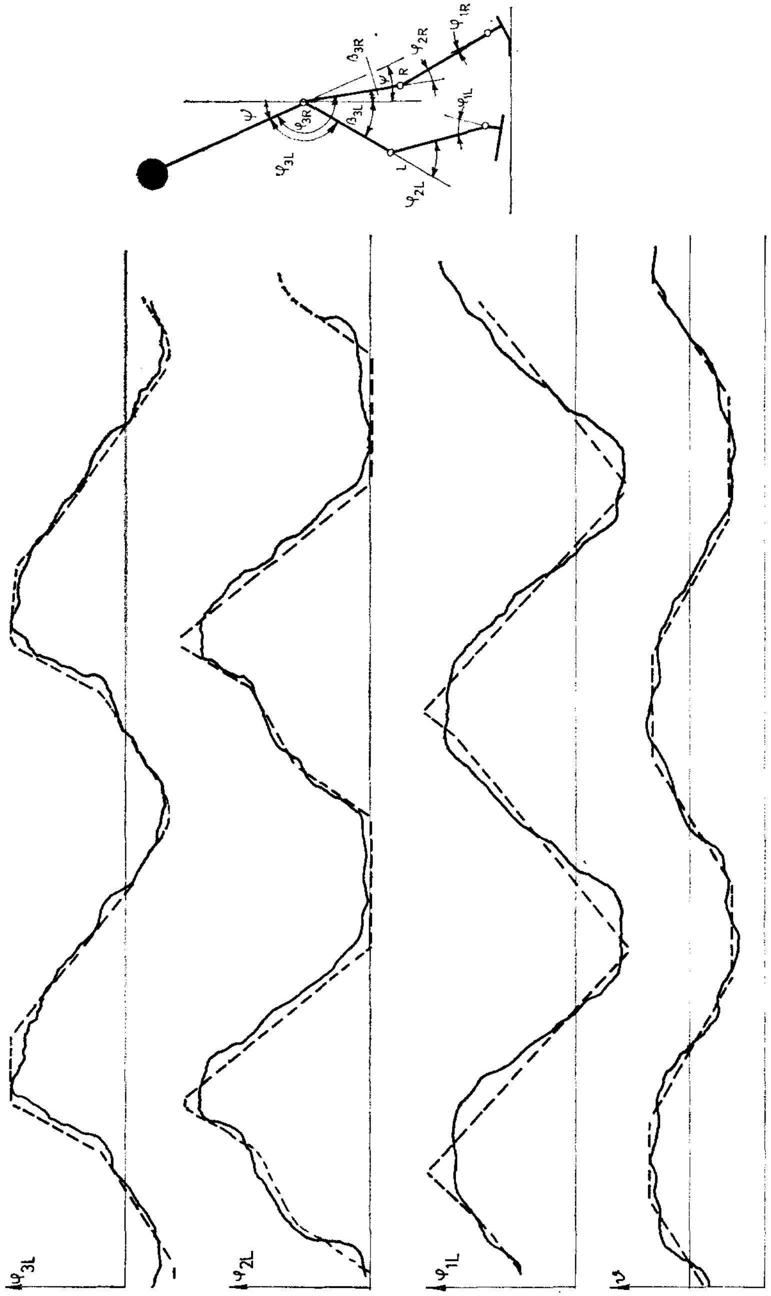


Fig. 15
Generated and recorded synergy
- - - generated 'internal' synergy
—— recorded 'internal' synergy

given as

$$\left.\begin{aligned}\Delta M_X &\approx \frac{\partial M_X}{\partial \ddot{\psi}}\Delta\ddot{\psi} + \frac{\partial M_X}{\partial \ddot{\upsilon}}\Delta\ddot{\upsilon} + \sum_{i=1}^{6}\frac{\partial M_X}{\partial \ddot{\beta}_i}\Delta\ddot{\beta}_i \\ \Delta M_Y &\approx \frac{\partial M_Y}{\partial \ddot{\psi}}\Delta\ddot{\psi} + \frac{\partial M_Y}{\partial \ddot{\upsilon}}\Delta\ddot{\upsilon} + \sum_{i=1}^{6}\frac{\partial M_Y}{\partial \ddot{\beta}_i}\Delta\ddot{\beta}_i\end{aligned}\right\} \quad (13)$$

Thus it is assumed that the internal algorithm develops precisely by means of special tracking systems, and that the change in acceleration occurs simply because of the appropriate change in forces. If we extend this assumption further, it is natural to assume that all increments of acceleration of all elements of the anthropomorphic mechanism in the sagittal plane are identical; i.e.

$$\Delta\ddot{\psi} = \Delta\ddot{\beta}_i$$

In that case, solving eqn. 13 for the accelerations in the sagittal and frontal plane, we get

$$\Delta\ddot{\psi} = \frac{\Delta_1}{\Delta} \qquad \Delta\ddot{\upsilon} = \frac{\Delta_2}{\Delta} \quad . \; . \; . \; . \; . \; . \quad (14)$$

where

$$\left.\begin{aligned}\Delta_1 &= \Delta M_Y\frac{\partial M_X}{\partial \ddot{\upsilon}} - \Delta M_X\frac{\partial M_Y}{\partial \ddot{\upsilon}} \\ \Delta_2 &= \Delta M_Y\left(\frac{\partial M_X}{\partial \ddot{\psi}} + \sum_{i=1}^{6}\frac{\partial M_X}{\partial \ddot{\beta}_i}\right) \\ &\qquad - \Delta M_X\left(\frac{\partial M_Y}{\partial \ddot{\psi}} + \sum_{i=1}^{6}\frac{\partial M_Y}{\partial \ddot{\beta}_i}\right) \\ \Delta &= \left(\frac{\partial M_X}{\partial \ddot{\psi}} + \sum_{i=1}^{6}\frac{\partial M_X}{\partial \ddot{\beta}_i}\right)\frac{\partial M_Y}{\partial \ddot{\upsilon}} \\ &\qquad - \left(\frac{\partial M_Y}{\partial \ddot{\psi}} + \sum_{i=1}^{6}\frac{\partial M_Y}{\partial \ddot{\beta}_i}\right)\frac{\partial M_X}{\partial \ddot{\upsilon}}\end{aligned}\right\} \quad (15)$$

Taking into account eqn. 10, it is possible to obtain the relationship between the accelerations:

$$\ddot{\phi} = B^{-1}\ddot{\beta} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (16)$$

With regard to the system of eqn. 9, it is possible to define the compensating driving torques in the function of the increments of acceleration of the 'internal' synergy:

$$\Delta M = A\Delta\ddot{\phi} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (17)$$

where $A = \|a_{ij}\|$ and $a_{ij} = \partial M_i/\partial\ddot{\phi}_j$.

Combining eqns. 16 and 17, the important relationship is obtained that serves as the basis for deriving the stabilisation algorithm:

$$\Delta M = AB^{-1}\Delta\ddot{\beta} \quad . \; . \; . \; . \; . \; . \; . \; . \quad (18)$$

$\ddot{\beta}$ represents the complete set of the external coordinates of the system. In the case considered, the increments of the acceleration of the external coordinates are $\Delta\ddot{\psi}$ and $\Delta\ddot{\upsilon}$.

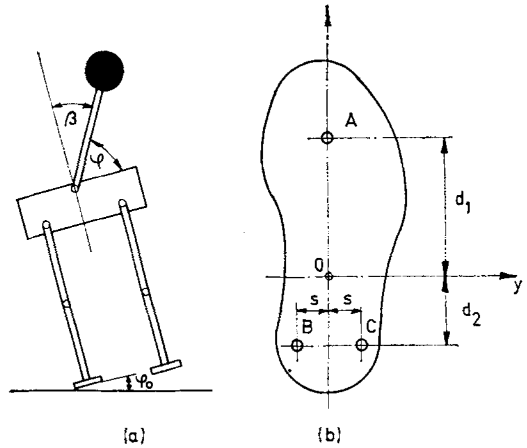


Fig. 16 Schematic illustration of vertical reactions

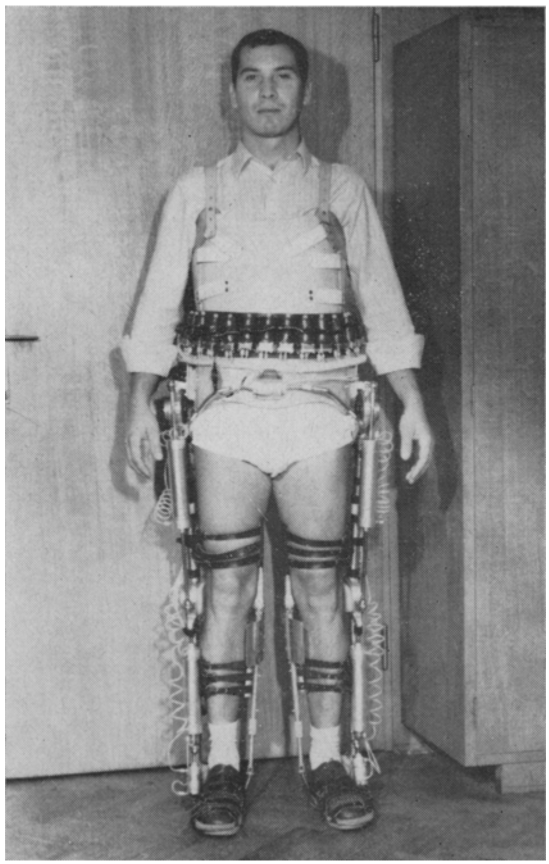


Fig. 17 Healthy person in exoskeleton

In the majority of cases the patients favourably accepted the machine in its present form, and did not reject it after prolonged and repeated trials.

A comparatively high level of reliability of the whole technical system has been attained, enabling uninterrupted trials of two hours' duration and more.

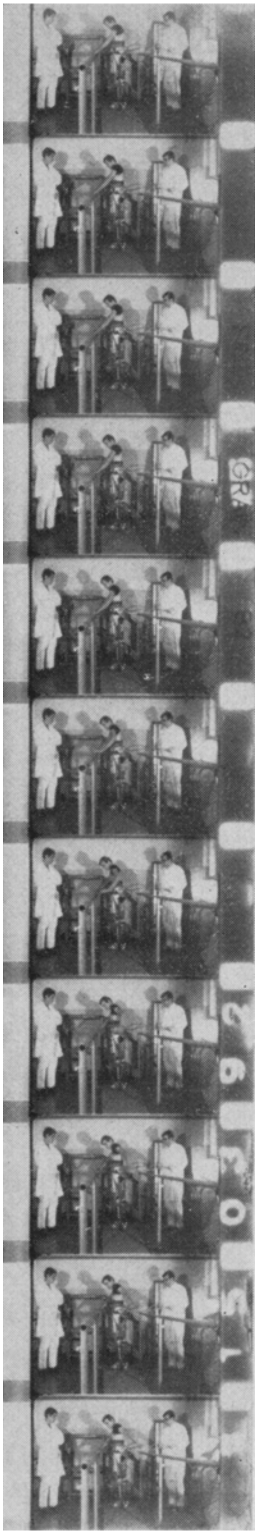


Fig. 20 Film insert from clinical trials

Conclusion

The results presented in this paper illustrate the efforts made over many years to realise an active orthotic system, which could be applied to the rehabilitation of handicapped persons. The basic aim is to release the paralysed paraplegic person from the wheelchair, the only existing means of locomotion which is available in closed environments. Since only the opinions of medical experts and paralysed patients are conclusive as to the final success of the project, it must be confessed that the problem has not by any means been solved. In other words, the exoskeleton, as a means of rehabilitation, is by now at the start of a systematic clinical evaluation. It should be emphasised that the exoskeleton is, in its present state, capable of enabling the gait upon level ground aided by supporting canes of a paraplegic patient with a high lesion. These canes do not introduce any driving energy, but play the role of the simplest 'stabilising system'.* At the same time, control schemes for perturbed working regimes were being developed, thus initiating work on the realisation of the automatic maintenance of dynamic equilibrium. In this phase of the investigation, force feedback, obtained by measuring the dynamic reactions at the contact point, together with the support measurement, has proved to be a fairly reasonable parameter. Thanks to this control scheme, up to the present, gyroscopic instruments for the assessment of stabilisation correction signals have not been necessary.

Further evaluation of the exoskeleton will be continued with the aim of prolonging the gait phase upon level ground and performing the action of ascending and descending stairs. Also the compensating system will be further developed, since its realisation has been based on measuring dynamic reactions during the gait.

In the forthcoming 3-year project, which will continue to be supported financially by the Social and Rehabilitation Service, Washington, DC, the final goal is to provide for the paraplegic a safe gait upon level ground and stairs using canes, the only purpose of which are to secure microcompensation of the regulating system. By keeping to such a simple 'correction' system, the project becomes realistic, because it makes it possible to do without the very complicated and economically unjustified computer system which could produce 'exact' automatic balancing.

** It has to be emphasised that, for feedback involved by dynamic reaction, it is necessary to 'correct' the automatic stabilisation due to imperfections of the servo system*

On the other hand, the question still remains as to how much has got to be done in this field of robot application in order to allow the paraplegic to be able to leave his wheelchair. This question cannot be fully answered without several years of systematic investigation of the system in other orthopaedic centres. At present it is evident that, in the realising of an artificial gait for paraplegics, the patients themselves can be given as a free parameter only the decision on the type of action. It seems that this means for restoring locomotion properties to severely handicapped persons must be developed until the fundamental problem of sensory feedback is solved. Only then it will be possible to establish a natural relationship between the patient's intention and the machine that makes his desired movements possible.

Acknowledgment—The work was done, and the paper was written, under support by a Grant of the Social Rehabilitation Service, Washington, DC.

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Le développement d'exosquelettes anthropomorphes actives

Sommaire—Les postulats servant de base à cette nouvelle approche à l'étude de la dynamique des systèmes anthropomorphes sont explicités dans cette communication. Par rapport aux autres tentatives, cette approche rend possible une réduction maximale de dimensionnement en prenant comme point de départ l'attribution du phénomène de synergie à une quelconque partie du système. A titre d'illustration de la méthode considérée, il est fourni une synthèse synergique complète de la configuration retenue pour les systèmes anthropomorphes.

Die Entwicklung von aktiven anthropomorphen Gliederfüssern

Zusammenfassung—Die Grundpostulate dieses neuen Versuchs einer Studie der Dynamik von anthropomorphen Systemen werden in dieser Arbeit dargelagt. Im Vergleich zu anderen Versuchen macht dieses Vorgehen eine weitestgehende Reduzierung der Dimensionalität dadurch möglich dass, es sich darauf stützt, einem Teil des Systems Synergie zuzuschrieben. Als Illustration der Methode wird ein Beispiel einer vollständigen Synergie-Synthese für die angenommene Konfiguration des anthropomorphen Systems angeführt.