LEGGED LOCOMOTION

DEVELOPMENT OF ACTIVE ANTHROPOMORPHIC EXOSKELETONS

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Summary

The basic theoretical postulates for the synthesis of a new kind of assistive rehabilitation device for paraplegics, or human beings with insufficient muscle power of biological actuators are set forth. The synthesis of such systems has resulted in an artificially strengthened skeleton, called the exoskeleton. Described, also, is the development of the first version of the exoskeleton subsequent to the demonstration at the Third Symposium on External Control of Human Extremities, in Dubrovnik, 1969. The latest version of the complete anthropomorphic mechanism is described in detail. This mechanism makes performance of all of the elementary locomotive actions possible.

Introduction

Any attempt to achieve the synthesis of the locomotor mechanism of the human leads to the formulation of incredibly complex systems, particularly from the control point-of-view. For this reason, in the synthesis of anthropomorphic mechanism, the objective has been to produce only a limited amount of elementary human locomotive functions, such as gait.

The basic problem in the synthesis of such an artificial anthropomorphic system has been to generate appropriate synchronized movements called the artificial synergy of the locomotion system.

The basic concept is to set in advance the law of the so-called zero-moment point* transfer. In this way and in com-

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*The zero-moment point is the point of contact between the lower extremity and ground at which the resulting force of reaction acts.

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pliance with D'Alambert's principle, the sum of the moments of external and internal forces with respect to the system of coordinates connected with the points mentioned, gives particular conditions of dynamic equilibrium, the so-called dynamic relations /1,2/. In the case the locomotion system would have three degrees of freedom only, by intergrating the obtained dynamic relations it is possible to determine the laws of change in the corresponding angular coordinates.

However, the number of degrees of freedom, n, is by rule considerably greater than three, and the law of change in the remaining /n-3/ coordinates should be set as such to provide the gait, that is, the periodic transfer of legs, the appropriate change of single- and double-support phase, and the like. Most purposeful is to get this information by studying directly the human gait. We know now how man walks, but, we are not able to explain the reason for the gait observed. Therefore, the attempt to get directly the laws of change in all coordinates based on the minimization of some global criteria is slightly justifiable. It is evidently more purposeful to register on the man the laws of change of the leg coordinates. Thus it is possible to set laws of change in /n-3/ coordinates of a robot.

The synthesis of artificial synergy is carried out in two ways. For a part of the coordinates there is a fixed program of motion. The laws of change of the remaining coordinates are determined from a.m. equations of dynamic relations.

Roughly speaking, the gait diagram in this case would be as follows: "the legs" change to some algorithm recorded from the man, and "the body" performs periodic compensating motion thus providing the appropriate system equilibrium in the saggital, frontal and horizontal plane. This contribution will not deal with the theoretical fundamentals of this approach because they have been treated rather sufficiently in other papers /1,2,3,4,5,6/.

Development of Active Exoskeletons

The first version of an exoskeletal type of rehabilitation device is the Kinematic Walker (Fig.1).

The Kinematic Walker had one degree of freedom for each leg, and in compliance with this, one pneumatic cylinder-type ac-

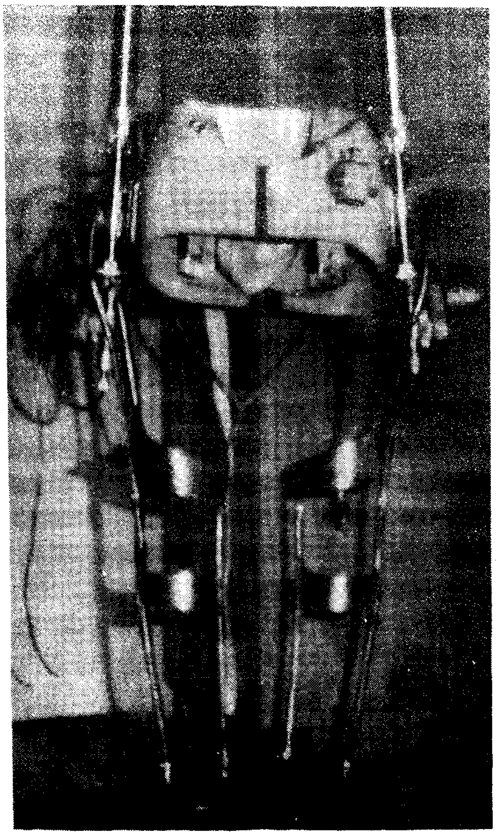

Fig. 1. Kinematic walker (1969)

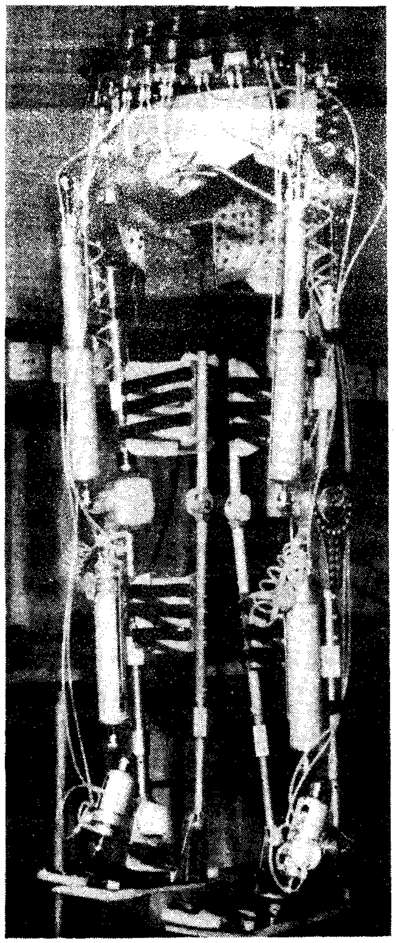

Fig. 2. Partial exoskeleton (1971

tuator for each leg and a pure kinematic link of the joints. Due to the need for an uprights (standing) position, the gait performed was very similar to the initial gait algorithm on level ground, being defined with only two parameters, α and T / 1 /. The first experiments with this device were carried out in the Orthopaedic Clinic with two patients during 1969 and 1970. The results were very modest: the patient "walked" assisted by two male nurses. Certain experience was also acquired in regard to the attachment problems.

The next model of partial active exoskeleton /Fig.2/ made it possible to realize synergy of legs with three degrees of freedom, while the hip joints had two degrees of freedom and a joint drive in frontal plane, whereby it was also possible to achieve compensation in that plane /angle ν/. Clinical tests with this model were performed during 1971 with three patients. The gait of the patients was considerably better, and knowledge of the phenomenon of the transfer of forces from the machine to the man, and vice-versa, was gained. With the exception of the corselet and the control system, this model is very similar to the newest model, the Complete Active Exoskeleton /Fig.3/.

The Complete Active Exoskeleton is intended for rehabilitation of paraplegics with relatively high lesions involving muscular activities of legs and the waistpelvic part. In addition to the control of legs, the control of the upper part of the body is also made possible. Thus the gait algorithm is obtained as prescribed.

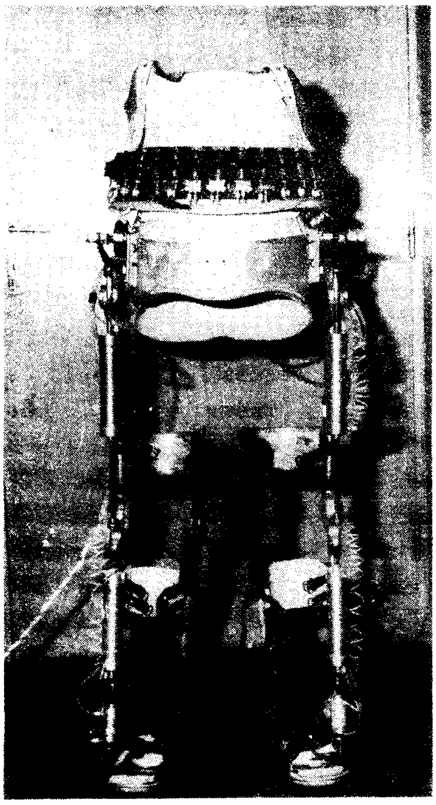

Fig. 3. Complete exoskeleton (1972)

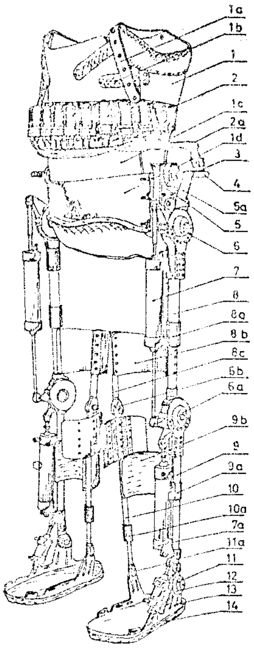

Fig. 4. Complete exoskeleton design

The complete exoskeleton is made up of three main subassemblies: corselet with the adjoined subassemblies, and left and right "leg" /Fig.4/. The corselet (1) was made using standard techniques of polyesther resin reinforced by polyamide fibers. The corselet envelopes the body of the patient from his public-ischial part up to the underarms, over the chest and back. It is fastened over the shoulders by means of leather straps (1a). The front part (1c) of the corselet is a separate unit, and is fastened by VELCRO strips (1b) to the dorsal part. The ventral part of the front cover (1d) is reinforced by a formed piece of duralumin sheet in order to increase the stiffness of the corselet pelvic part. A leather belt (2) containing 14 electropneumatic 3-way valves for controlling six pneumatic cylinders (3 per leg) and two membrane actuators (3) is fastened to the corselet. The pneumatic pulses are conveyed from the electropneumatic valves to the cooresponding actuators through 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 (about the longitudinal axis). By means of the lever (5a) belonging to the "leg" subassembly, the drive of the membrane actuators (3) is transmitted to both legs and synchronized by means of the lever (4) surrounding the corselet from the back 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), 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, with teflon sliding surfaces adjustable friction. The precision feedback potentiometer is located in the central hole. Its "zero" can be adjusted from the outside. The elements connecting the base elements of the corselet with the joint (6) stationary part (cup), are fastened to the latter, as well as the lever connecting it to the actuator (7). The actuator is manufactured of 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 two-member telescopic tube made of inox steel (wall thickness, 0.8 mm), the length of which can be adjusted to the patient by means of a knurled nut (8a). The leg support (8b) is made of inox steel sheet and covered with sponge rubber. This part is fastened to the other part of the femoral "bone" (8) and the auxiliary strut (8c).

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

The "foot" of the leg is connected by means of the "ankle joint" (11) and the auxiliary joint (11a) to the "shank" part of the "leg". Each joint contains a feedback potentiometer. The actuator of the "foot" (12) is of a design very similar to that of the other actuators (7 and 7a), but is of smaller diameter and is shorter. The "foot" (13) itself, is made of inox sheet, stiffened by drawn ribs and swaged edges, and covered on the upper side with expended plastic 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, that provides a certain adaptivity in the frontal plane. On the lower side of the "foot" (14) there are three force transducers with strain gauges 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.5). In this way it is possible to know at every moment the intensity and position of the vertical component of the resultant force of the system acting on the foot. These data will be used in the synthesis of the regulating system.

Electronic System for Complete Exoskeleton Control. A block-diagram of the control system for complete synergy of the active exoskeleton is given in Figure 6. The left leg time base generator, TBGL, represents the source of the synchronizing frequency. Period T can be adjusted in the interval of 1 to 5 sec. The elec-

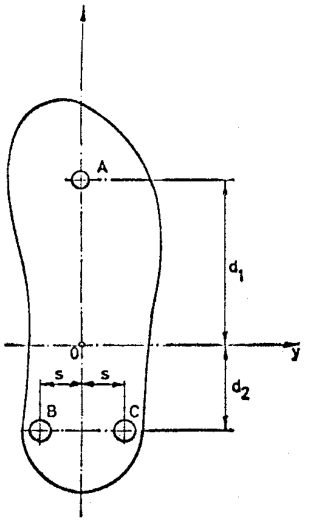

Fig. 5. Schematic illustration of vertical reaction components measurement

tronic circuit of the right leg time base generator, TBGR, is a time delay circuit. The output signals of the circuits TBGL and TBGR are connected by the expressions: $V_R(t) = V_L(t+T/2)$.

Figure 6 shows all seven servosystems for controlling the time functions of the characteristic angles of the joints $\phi 1L'$ $\phi 2L'$ $\phi 3L'$ $\phi 1R'$ $\phi 2R'$ $\phi 3R$ and θ. The synchronism of the angles time functions is preserved by the very fact that all function generators are strictly interconnected in time by means of electronic circuits TBGL and TBGR. To be more precise, the reference inputs of the servosystems are synchronously linked, whils the synchronism of the real angles depends both on reference inputs and the characteristics of the servosystems realized.

Operation of Exoskeleton Control System. The prescribed leg synergy and the calculated compensation synergy are generated by electronic transistorized function generators. The internal angles (ϕ_i) are generated for the ankle and knee joint, whereas the internal angle for the hip joint, having two degrees of fre-

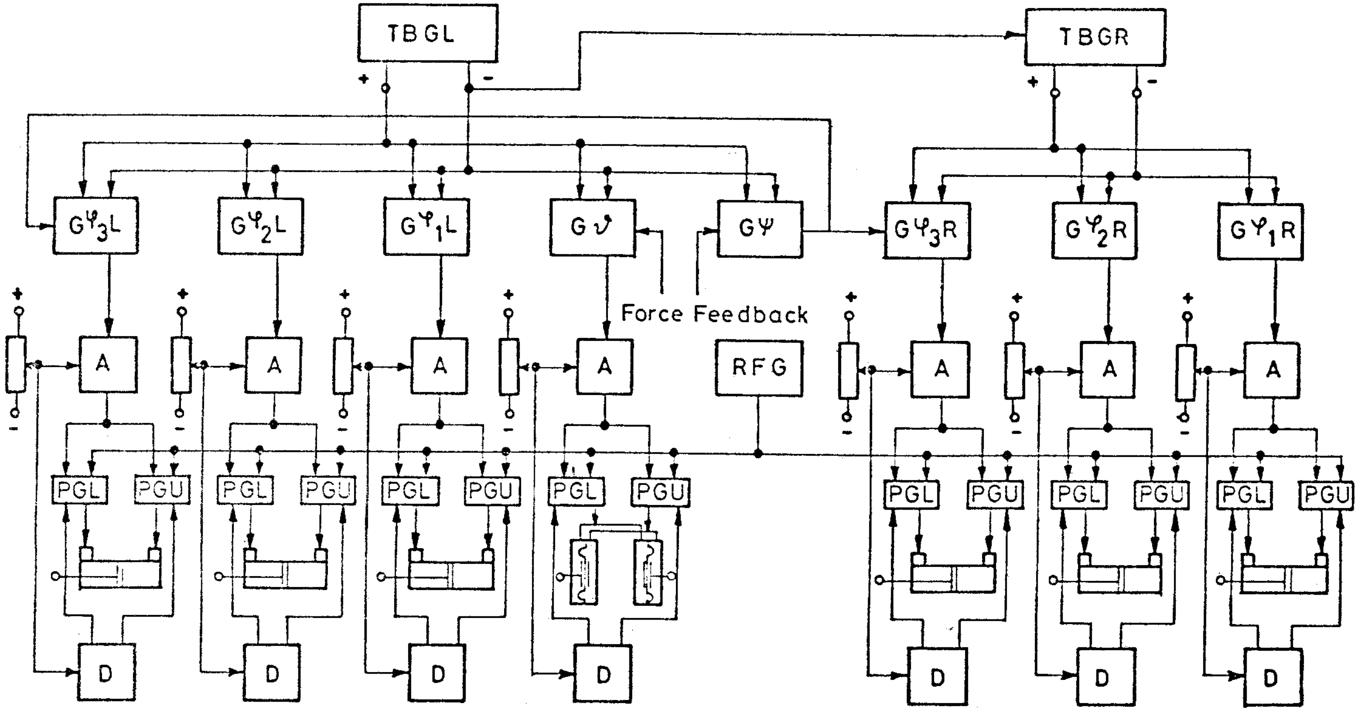

Fig. 6. Block diagram of complete exoskeleton synergy realization

edom, is obtained as the algebraic sum of the hip joint angle (absolute coordinate $\beta_{3L,R}$) and the compensation coordinate in the sagittal plane (absolute angle Ψ, Fig.6). For the laternal compensation, the compensation angle in the frontal plane, υ, is generated by a separate function generator.

The signals from the seven function generators, are fed into the control system, serving as leading signals in this tracking system. Local feedback loops, formed by servopotentiometers in the joints, transmit the position and, through differential relays velocity feedback signals into the control system, where the positions are compared with the input (leading or prescribed) signals and the error or deviation is formed. After amplification and correction with respect to the velocity (gradient), this error influences the sign and width of a constant frequency, pulse-width modulated output, which activates the electromagnetic valves, admitting compressed air from the proper side and in proper quantity into the actuators.

Figure 7 illustrates the electronic realization of the prescribed and compensating synergy. Also, the realization of the complete synergy, measured by means of the servo-potentiometer system during the gait of the anthropomorphic system exoskeleton - patient, is shown. The measured (realized) synergy is, naturally, expressed in "internal" angles. For this reason, the electronic realization of the prescribed program is given in internal coordinates, too.

The practical realization of the complete exoskeleton is illustrated in Figure 8 with a healthy person in it, and in Figure 9 with a paraplegic patient. Every detail of the conception, described in the preceeding text, has been realized. Great care has been dedicated to the weight problem. The whole structure in the present version weighs approximately 30 lbs., which could be reduced considerably by applying recently developed modern constructional materials, like metalplastics, rainforced polyesther residue, etc.

Time needed to mount the exoskeleton onto the patient is somewhere about 7 minutes and in the present state, the help of a trained person is necessary. By many refinements and application of simpler subassemblies and links, it is anticipated the

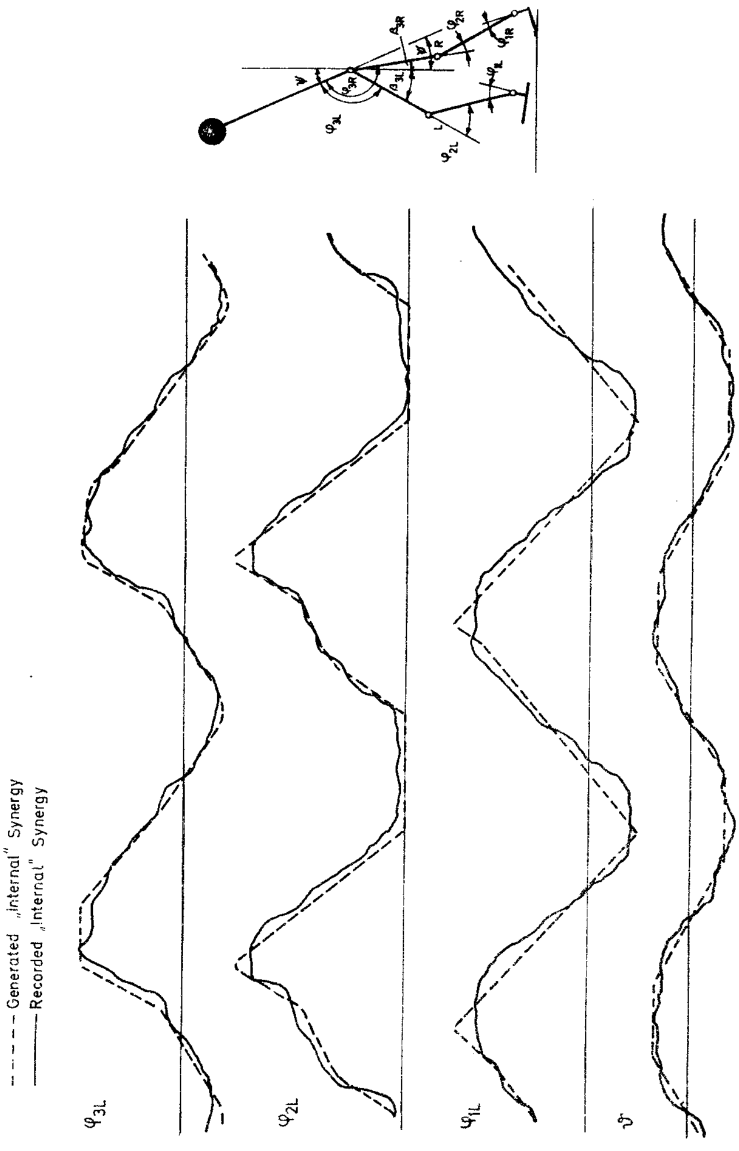

Fig. 7. Generated & recorded synergy

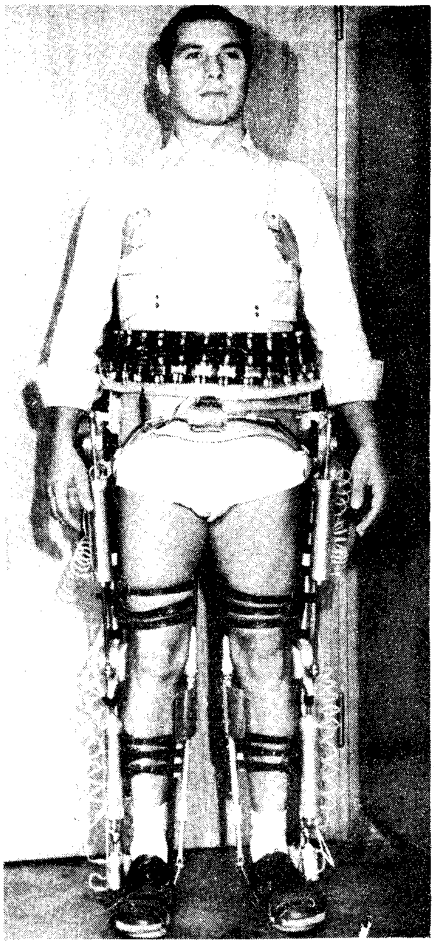

Fig. 8. Healthy person in exoskeleton

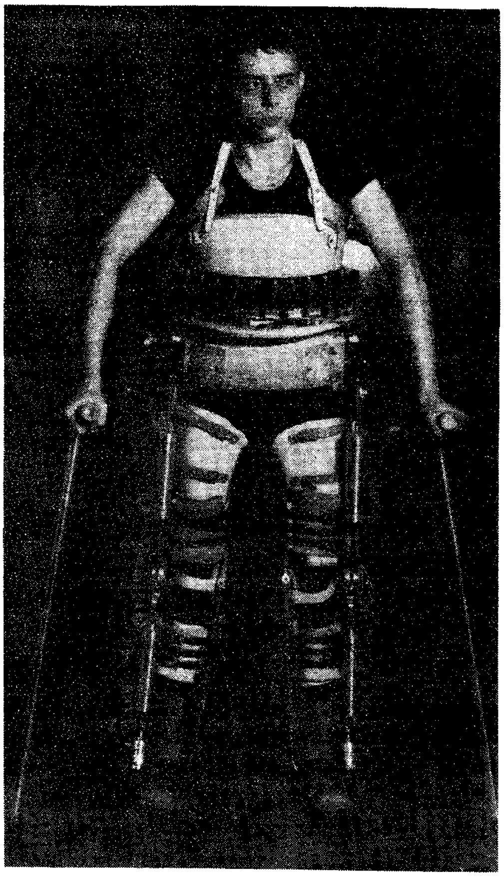

Fig. 9. Patient in exoskeleton

problem of self-mounting of the machine to his body by the patient himself can be solved in one year.

The clinical tests, carried out during the last year in the Orthopaedic Clinic in Belgrade with several paraplegics have shown the following encouraging results:

- quite dependable walking on level ground has been achieved, the patient walking between bars of a special pathway
- the development of the corselet and the force-transfer points of the machine to the body of the patient has attained the point of practical absolute freedom from the danger of decubital phenomena,

- the patients accepted the machine in its present form in the majority of cases favourably, not rejecting it after prolonged and repeated trials,
- the dependability of the whole technical system has attained a comparatively high level, enabling uninterrupted trials of period up to two hours.

Conclusion

The results presented in this paper illustrate the effort of many years in the development of an active orthotic system that can be applied in the rehabilitation of handicapped persons. The basic trend lies in making the paralysed person of the paraplegic class less dependent on the wheelchair, the only existing locomotion means presently available. Only medical experts and paralysed patients are competent to judge the final success of this attempt. The exoskeleton, as a rehabilitation device is now at the beginning of a systematic clinical evaluation. It should be underlined here that the exoskeleton is in this early phase capable of making possible gait on level ground aided by supporting canes in the case of a paraplegic patient with high lesion. These canes do not introduce the driving energy, but play the role of the simplest "stabilizing system". At the same time, control schemes of perturbed working regimes were elaborated, initiating the efforts in the realization of dynamic equilibrium automatic maintenance. It should be emphasized,that in this phase of the investigations a force feedback, realized via dynamic reactions at the contact point with the support measurement, has proven to be fairly reasonable. Thanks to this control scheme, gyroscopic instruments for stabilization correction signal assessment were avoided.

The approach to the synthesis of such a rehabilitation system has its deficiency in the fact that with the complete version and the system for automatic equilibrium maintenance engaged, the role of the patient is reduced to the role of a mere observer of the experiment being conducted upon him. However, in compliance with the present situation of such devices development one can get an impression that for paraplegics with a high degree lesion of the spinal column the procedure exhibited is the only potential possibility to have them rehabilitated. Any introduction of the so-called "flexibility" into the system paraplegic - machine, would lead to a considerable uncertainty of the experiment.

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