FUNCTIONAL ORTHOTICS OF UPPER EXTREMITIES

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The purpose of this work undertaken by the research group was to design, to fabricate and to give an invalid (tetraplegic) a device which could make him partly independent for activities of daily living. The efforts were made in two directions: to enable the invalid to move without any assistance and to enable him to perform the simplest motions of the upper limbs necessary for carrying out substantial functions.

The first problem has been solved by fitting an electric wheelchair with a simple control system, the second has been overcome by application of adequate apparaturs driven by artifical muscles controlled mechanically or bioelectricaly by the patient. The control system enables the invalid to chose a set of motions by activating levers with slight motions of his head.

The experiments show that after relatively short training time the patient easily makes use of the apparatus and performes simple functions, feeds himself, shifts objects from hand to hand, types, etc. The first test-runs confirmed that the apparatus is very useful. Clinical observations and investigations are now being carried out to modernize various subassemblies.

1. General Biomechanical Assumptions

In design and application of devices replacing lost functions the following problems should be considered:

- the number of degrees of freedom, importance of the lost function, functional ranges of motion in joints and forces and power necessary for carrying out essential functions by the patient,
- design of apparatus with respect to its usefulness, comfortable wear and proper cosmetic appearance,
- the proper drive and supply system: patient's muscles, electric power, compressed gas, etc.
- the proper control system: pull rod, bioelectric, myotonic, external programme (electric, mechanical)
- operating conditions and reliability of a device
- physical and psychological adaption of a patient to a device

The total number of degrees of freedom of human limbs is 30 /1/. The distribution of degrees of freedom for the upper extremity is the following: hand (manus) has 23, shoulder joint 3, elbow - radial joint - 1, and carpus-radial joint - 2.

It is possible to design a device having 30 degrees of freedom, but such a great number of degrees of fredom cannot be, so far controlled. In other words, the nervous system of a man cannot be replaced. For these reasons designers confine themselves to replacing only grasping movement (1 degree of fredom) assisted by functions of other joints of the upper limb, (such as flexion, abduction, and pronation). Thus a simplified model has 7 or 8 degrees of freedom. Assuming that various joints have from one to eight functions /2/ the possible number of apparatuses is:

$$\sum_{k=1}^{k=8} C_8^k = 2^8 - 1 = 255 \qquad (1)$$

It is very difficult to fabricate so many versions of apparatus. In order to decrease the number of versions let us systematize functions in order of their importance. The criterion of importance is the useful area covered by the hand while moving an arm in a given joint within its possible range. The graphical analysis has

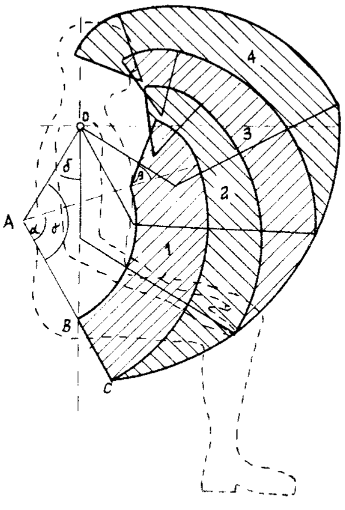

Fig. 1. Example of graphical analysis applied to determine the useful area: O - shoulder joint axis B - elbow joint axis, C - tip of the third finger

been made in sagital (flexion and extension), frontal (abduction and adduction), and horizontal (pronation and supination) planes /3/. This analysis makes it possible to calculate the necessary angles in joints in order to bring the hand to the desired position about the trunk, neck, and head of the patient, and to evaluate his possibilities.

Figure 1 presents the analysis of the useful area of the hand for various angles of rotation and initial position of elbow and shoulder joints /4/. The area 1 equal to 1070 cm^2 (Fig. 1) is covered by the hand when the arm bone is withdrawn by 30°, position of the elbow joint $\gamma = 120^{\circ}$, range of motion 80°, and the range of motion for carpus-radial joint $\beta = 50^{\circ}$. The increase of motion in elbow joint by $\delta = 30^{\circ}$ is followed by an increase of useful area by 800 cm^2 (area 2 in Fig. 1). In the result of analysis the lost functions should be replaced in the following order:

1 - grasping,
2 - flexion and extension in elbow joint,
3 - flexion in shoulder joint,
4 - abduction and adduction in shoulder joint,
5 - pronation and supination in shoulder joint,
6 - pronation and supination of forearm,
7 - flexion in carpus-radial joint,
8 - Abduction and adduction in carpus-radial joint.

The number of versions of apparatuses may be considerably reduced if the functions of the shoulder joint are neglected. These functions can be compensated for by motions of the shoulder blade and the trunk when the shoulder joint is immobilized. In this case the number of degrees of freedom is 5 with 31 possible versions of apparatures according to Formula 1. Further reduction of the functions is possible for less important functions (for example 5 and 8).

2. Case Study

The patient is an 18-year old male. As a result of poliomyelitis his limbs are paralyzed. He cannot move, and after surgical stiffening of the vertebral column can sit in a wheelchair. His neuromuscular picture is as follows: motion of the upper part of the neck, residual motion of the left shoulder, poor flexion of the left arm, extension performed in the carpus-radial joint, and partial supination of the left forearm. The right upper limb shows zero motion. The patient is intelligent, attends high school, and collaborates very well with the doctors and engineers in order to become independent.

Before fitting the patient with a special equipment wide studies had been carried out. Based on these studies, a set of active and passive motions was selected to be performed with the help of auxiliary devices (Table 1).

3. Design of Auxiliary Devices

The design of the apparatus enables the patient to perform both active and passive motions described in Table 1.

Table 1

Upper left extremity		Upper right extremity	
active motions	passive motions	active motions	passive motions
1. Grasping. Motion range (opening) 60°	-	1. Grasping. Motion range (opening) 60°	1. abduction and adduction in shoulder joint. Motion range about 60°
2. Lifting and lowering of the extremity; Motion range about 15 cm	-	2. Flexion and extension in elbow joint. Range about 110°.	2. Rotation in the shoulder joint. Motion range about 90°.
		3. Lifting and lowering of the extremity. Range about 15 cm.	

This design enables the patient to perform simple motions necessary for feeding himself, turning the pages, writing with left hand and holding light objects /5, 6/.

The general view of the wheelchair and auxiliary appararatus is shown in Figure 2. The right handsplint is mounted on the wheelchair by means of the bracket 1. In this design the axes of the joints 2 and 3 concide with the center of the patient's shoulder joint. Owing to the rotational connections 4 and 5 the patient can move his trunk to avoid fatigue. Elevation of the shoulder joint is performed by means of the muscle 8 fixed to the outrigger 7 ridigly connected with the patient's arm. The muscle 9 mounted on the outrigger 6 ensures flexing of the elbow joint. Fingers are bent by means of bellows 10 activating a special lever. Optimal setting of the apparatus is achieved by interlocking the joints 11 and 12 by means of special screws.

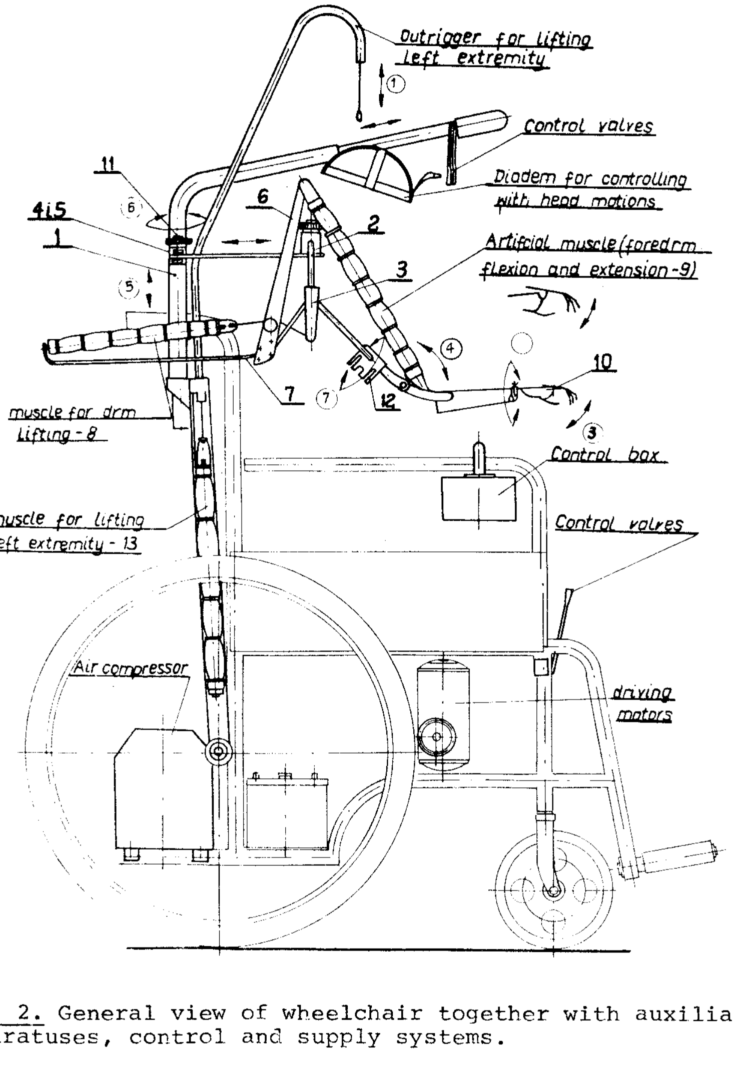

Fig. 2. General view of wheelchair together with auxiliary apparatuses, control and supply systems.

The outrigger carrying the cable operated by muscle 13 is mounted behind the back of the chair and is used for lifting and lowering the left limb. The limb is supported by an elastic band sliped on the elbow joint. The grasping motion of the left hand is performed similarily as for the right hand. Ball bearings were used to decrease friction.

4. Design of pneumatic muscles

Pneumatic artifical muscles (Fig. 3) having constant length of generating line were applied for performing active motions without grasping /7/.

The muscle consists of a rubber tube 1 within the wall of which inextensible threads 2 are placed. Both ends of the tube are fitted with duraluminium extensions. The ends of the tube are clamped by means of the caps 5 on the taped sections of the casings 3 and the extensions 7. The ends of the rubber tube are clamped on the stub pipes of the casing 3 and 7. The stub pipes machined in the casing are connected with the PVC hose for supplying the compressed gas. Special rings 4 are put on the tube to prevent expansion of the muscle near the extensions. The inner diameter of the rings are smaller then the external diameter of the cases of the extensions. The holes in the caps 5 and casing 3 are used for mounting the muscles. Increasing the pressure inside the tube causes its diameter to increase and its length to decrease to 60% of its initial length.

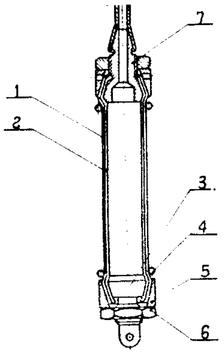

Fig. 3. Schematic of artificial muscle having constant length of generating line.

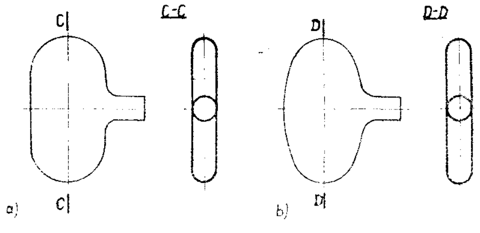

Fig. 4. Modifications of pneumatic bellows used for driving the grasping motion.

One of the greatest advantages of this muscle over McKibben's is very little hysteresis (about 1% is present). The permissible range of pressure for a muscle with a 1,2 mm thick wall is about 20-200 kNm^{-2}. It is quite easy to reduce the radial dimensions of the muscle by slipping on thetube a few rings and thus limiting its maximum diameter. The muscle takes then a form of several segments connected in series.

The muscle consisting of n segments has a leap equal to that of a one segment muscle but develops force n^2 smaller. Forces developed by these muscles are greater than forces developed by McKibben's muscles at the same pressure and with similar overall dimensions.

The artifical muscles were fabricated in a special way to ensure durability. After 200,000 cycles of operation the muscles have not shown any detorioration.

For performing the grasping motion, special pneumatic bellows were used (Fig. 4) /5/. The bellows were made of latex by moudling. The shape of the bellows is different for different purposes.

5. Control and Supply System

Control System

Considerable progress is being made with a continous control system if compared to impulse or bang-bang control.

Figure 5 shows two channels of control system. Each channel is a modification of a continous control system /5/. Control system applied to auxiliary device may include combined channels presented in Figure 5. Each channel is used for controlling angular position of the auxiliary device for a given joint.

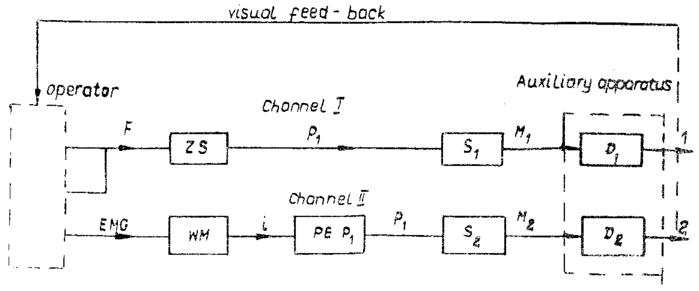

Fig. 5. Block diagrams of channels for motion control of auxiliary devices.

Input signal for the channel I is pressure force F exerted by the patient on the control valve ZS. The pressure p_1 of the air supplied to the artificial muscle S_1 is an output signal of the valve ZS. The muscle generates the torque M_1 acting on the driven member of the auxiliary device D_1. The channel described above has two feedback loops. The first is realized by the patient's vision who according to the results of control (angle α_1) changes signal F in order to obatin the desired α_1. The second is realized by skin sensitivity, and it enables the patient to control the pressure force F.

In the second channel the muscle myopotentials were used for control purposes. EMG signal resulting from the muscle tension is collected by electrodes, amplified, and properly formed by amplifier WM. Then, dependent upon the myopotential current, signal (i) controls the electro-pneumatic transducer PEP_1. The remaining parts of the II and I channel are identical. As in the case of I channel, the feedback loop is realized through vision.

Control Valves

The schematic of the control valve is shown in Figure 6. The operating principle is as follows: compressed air is supplied from

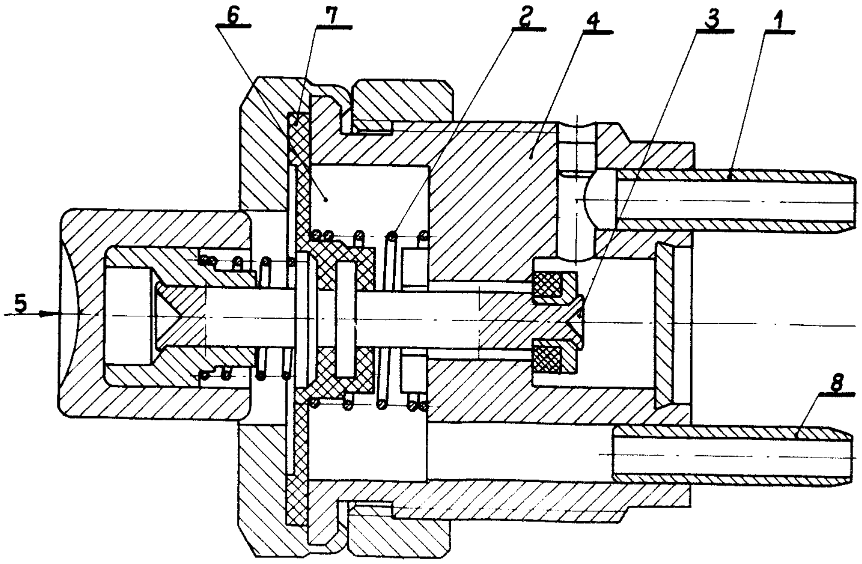

Fig. 6. Control valve.

the tank to inlet 1. Valve head 3 is pressed tightly against part 4 by spring 2. The valve is activated by pushing key 5. Then valve head 3 is separated from its seat and air fills outlet chamber 6 and acts on membrane 7, which is connected with the artificial muscle by means of extension 8. When the force exerted by the membrane is equalized by the force exerted by lever 5 on slide 3 the valve is shut. The area of the membrane and leverage were determined to keep the force F below 1.5 N.

Figure 7 shows the position of the valves. The patient pushes the keys 1 to 8 by means of the"beak" fastended to his head by a band. Valves 9 and 10 are activated by motions of patient's left hand.

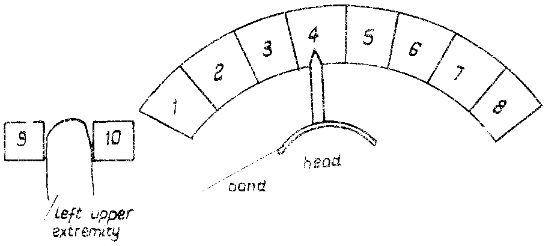

Fig. 7. Location of control valves

1 - opening of the left hand
2 - closing of the left hand
3 - lifting of the right arm
4 - lowering of the right arm
5 - opening of the right hand
6 - closing of the right hand
7 - flexion of the right arm in elbow joint
8 - extension of the right arm in elbow joint
9 - lowering of the left arm
10 - lifting of the left arm

The wheelchair is fitted with XB-08AB air compressor made in Poland (under a French licence). The compressor is driven by a 220 V AC electric motor. The compressed air passes through a filter and fills the tank of V = 5 l capacity. The air pressure is controlled automatically within the range of 2.2-2.6 ata (220 - 260 kN m^{-2}) by means of a special pressure switch which turns the compressor on and off automaticaly. The air tank is fitted with a safety-valve set for about 3 ata (300 kNm^{-2}). The compressed air is supplied to the control valves of artificial muscles by means of hoses. The first valve is used for shortening the muscle; the second is connected with atmosphere and is used for relaxing the muscle.

The air pressure inside the artificial muscle can be regulated continously by controlling the time of inflation and deflation of the muscle. The design of valves I and II is identical. The air tank filter and pressure switch constitute the integrated supply assembly mounted on the wheelchair.

6. Conclusions

A general view of the wheelchair and auxiliary devices is shown in Figure 8 /6/. Particular care was given to grasping mechanisms. The design presented in Figure 9 was finally accepted for application. Regardless of auxiliary devices the patient needs special extensions for different functions.

Figure 10 shows an example of adapting the apparatus to feeding by application of special extension for holding a spoon. Systematic training carried out for many weeks at the Rehabilitation

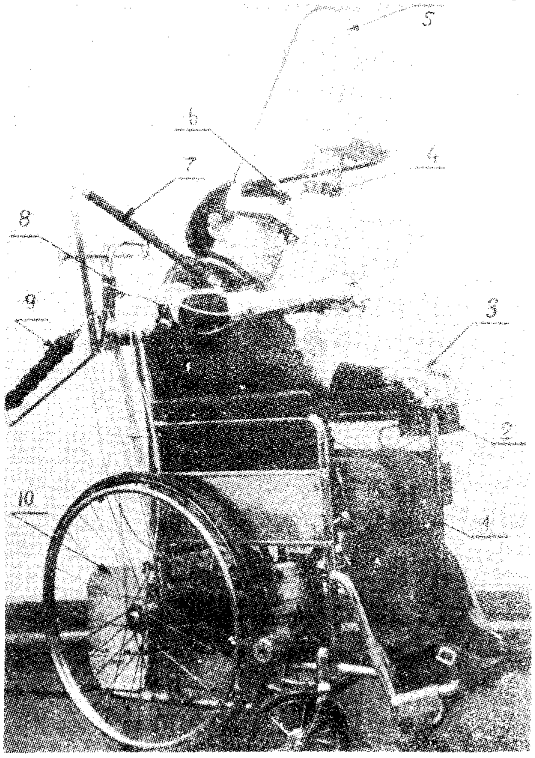

Fig. 8. Stationary multi-functional orthostesis.

1 - push button for controlling the lifting motion of the left arm
2 - drive unit
3 - pneumatic bellows for driving the grasping motion of the left apparatus
4 - location of the control valve
5 - cable for lifting left arm
6 - valve control device
7 - muscle for flexing the right extremity in the elbow joint
8 - mechanism of the shoulder joint
9 - bellows for lifting the right extremity
10 - supply

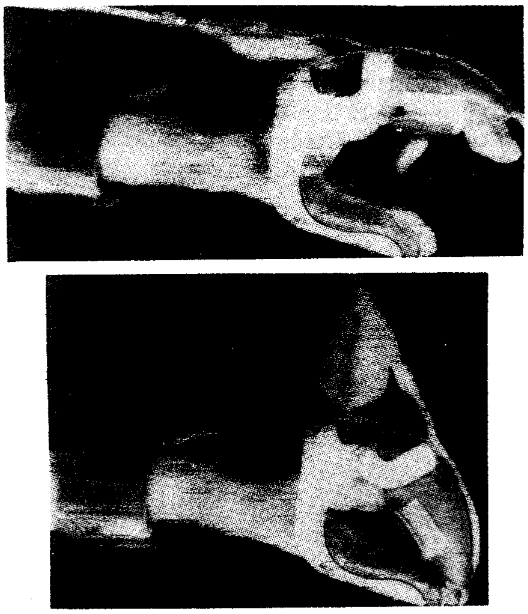

Fig. 9. Design of auxiliary device for grasping motion

a - initial position of the apparatus - hand fully open

b - final position - hand cleanched

Fig. 10. Left extremity extension - specialised for feeding

Clinic at Konstancin by mgr Skarzyński led to the following results and conclusions:

- the patient can control the consecutive active motions,
- the left extremity, having 3 physiological motions, is used as the primary tool while the total paralyzed right extremity is used as auxiliary,
- the patient can feed himself by means of spoon and fork. He uses an electric typewriter, lifts the receiver of a standard telephone and dials, turns pages of a book, picks a match from a match-box, and lights it, etc.

Obtained results are very promising and one may suppose that the patient will be able to learn other motions as required, and will be able to perform them quickly, precisely, and to control them subconsciously.

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