DEVELOPMENT ON EXTERNALLY POWERED ARTIFICIAL ARMS AT NBI*

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Introduction

Our laboratory started February 1, 1964. The background was the thalidomide disaster, and our main goal is still to provide the victims of this disaster and similar cases with externally powered prosthetic equipment, and of course to perform prosthetic research.

From the beginning we worked very closely together with the Swedish »Central Committee for Rehabilitation« (SVCR). Three persons, Mr. Stig Enger, Mr. Karl-Erik Klevebring, Ma. Eng, and Dr. Helmut Winderlich, are employed by SVCR and are working at our laboratory.

We also work in very close cooperation with the Eugeniahemmet (EH), which is a hospital and home for handicapped children and is responsible for the medical care of the dominant part of our Swedish thalidomide children. This means that EH has all the therapists preschool teachers, social workers and of course the different medical specialists, that make the necessary basis for our work. The head of EH, Dr. Stig Jonsäter, also has the orthopaedic responsibility for our experiments with patients.

At an early stage we realized the complexity of »Prosthetic Research«. New technologies are being introduced, and it is necessary that these different branches, such as control engineering, polymer technology, mechanical engineering, electronic engineering and mathematical physics are represented at an adequate level. It is also necessary to have a wide medical representation, like orthopedics, psychiatry, neurophysiology, allergology and pediatrics of course the knowledge and practical assistance of prosthetists, therapists and nurses.

By adequate representation we mean that specialized research and development should not be carried on by »amateurs«, guided by or

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consulting specialists, but by the specialists themselves at their institutions or in their industries. That, we think, is the only way to benefit from knowledge, tradition, skill and equipment. But this work has to be organized, and the projects must be realistic and significant for rehabilitation of amputees and the paralyzed.

Last spring a prosthetics research group, the »SVEN«-group, was founded in Stockholm. Permanent members are SVCR, EH and NBI, and associated members are »Research Institute for National Defence (FOA, Institutions at the »Royal Institute of Technology«, Stockholm and »Chalmers Institute of Technology«, Gothemburg, »Sahlgrenska Sjukhuset«, Gothemburg, »Prosthetic Laboratory«, Uppsala, Een & Holmgren Orthopaedic Company Inc., SAAB (manufacturer of aircrafts, electronic systems and motorcars), and the Technical Research Council of Sweden (TFR).

The SVEN-group has regular meetings, discussing mutual problems, analysing, evaluating, planning and coordinating projects, verifying applications for research grants, informing about running activities and collecting results from finished work. If the result is useful hardware or methods, the group organizes production and instruction.

Two further members of the SVEN-group will give papers at this symposium. Fredrik Möhl, who is a doctor and Ma. Eng. and head of the Prosthetic Laboratory in Uppsala, will demonstrate an electric hand orthosis, and Henry Lymark, senior research engineer at FOA, will discuss our, for the moment, biggest project, an electromechanical hand.

Amongst other topics I would mention signal processing, evaluation and electronic simulation of different control systems, including adaptive electropneumatic systems, development of a high-frequency electropneumatic on/off valve, development of cosmetic gloves with improved mechanical qualities and development of good, cheap seals for pneumatic actuators. A new project just in the process of being started is a psychological investigation of the attitude of the patient and the people surrounding him to the cosmesis of the prosthesis.

Now allow me to run into some of the topics at NBI.

Valves

At NBI some work has been done on the development of valves for pneumatic prostheses. It all started with an attempt to make a joystick controlled, two-dimensional four-element valve from the Hendon valve (Figs. 1 and 12). The work led to abandoning some of the principles of the original Hendon valve.

Figure 2 shows a cross-section of the simplest version of our four-way (or two-dimensional) valve. If the cross-section in Figure 2 is turned 90 deg. around the centre-line you will come to the two other plungers, as the valves are arranged in a square. The original Hendon valve is self-centering by springs. The size did not allow a similar design at the NBI valves. All four plungers are pressed up by the supply-pressure but stopped by the head of the centre screw. When the joy-stick is moved to the left, the plunger on the left side will be pressed down but the plunger to the right will not move. The self-centering action then is produced by the pressure under the plunger to the left.

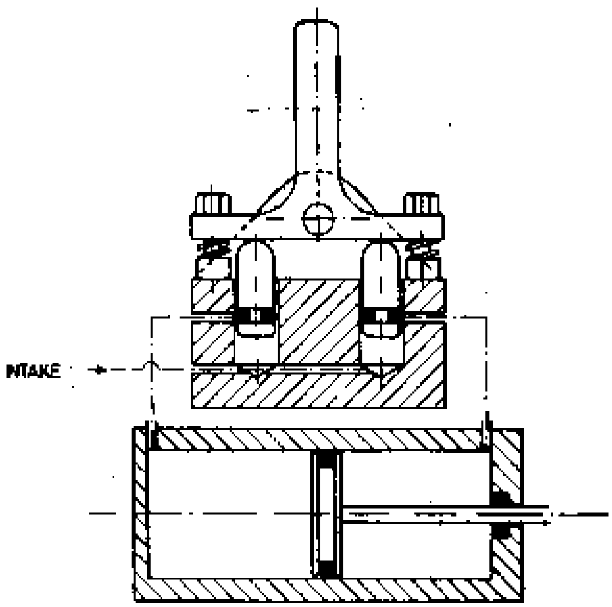


Figure 1. Hendon valve

For the moment two slightly different valve-bodies are used. The first version, (Fig. 2), has one outlet to actuators from each plunger. The second version, (Fig. 3), has two outlets in two opposite holes, and one outlet in each of the two other holes. The over-all-diameter of the bodies is 16 mm. Complete valves are shown in Figures 13, 14 and 15.

Four kinds of plungers, Fig. 16 all with a diameter of 2.5 mm, have been designed. Let us, before describing these plungers, try to classify the different pneumatic actuators which are in use today, and which the valves are intended to control (Fig. 4):

No. 1. Single-acting, with spring, gravity, or pneumatic return.
No. 2. Same as no. 1 but with pneumatically controlled lock.

No. 3. Double-acting, not self-braking.
No. 4. Double-acting, self-braking.
No. 5. Double-acting with pneumatically controlled lock.

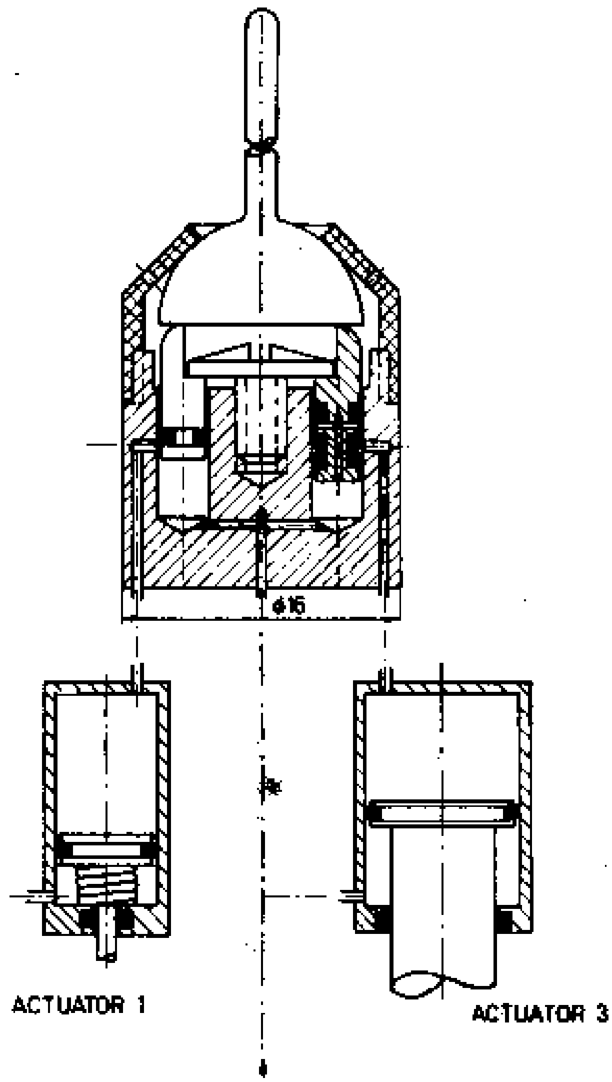


Figure 2. NBI four-way valve

Figure 5 A shows the original Hendon plunger. This plunger is designed to work in a plunger hole with one outlet. The centre screw in the valve body is adjusted to hold the O-ring at the plunger just above the outlet to the actuator. This means that full supply-pressure is connected to the actuator when the joy-stick is in its rest position. When the plunger is pressed down, the O-ring first closes the outlet to the actuator and then gradually connects the actuator to the exhaust of the valve. The scheme under the plunger in the figure shows as follows. The centre position of the joy-stick is represented by origin.

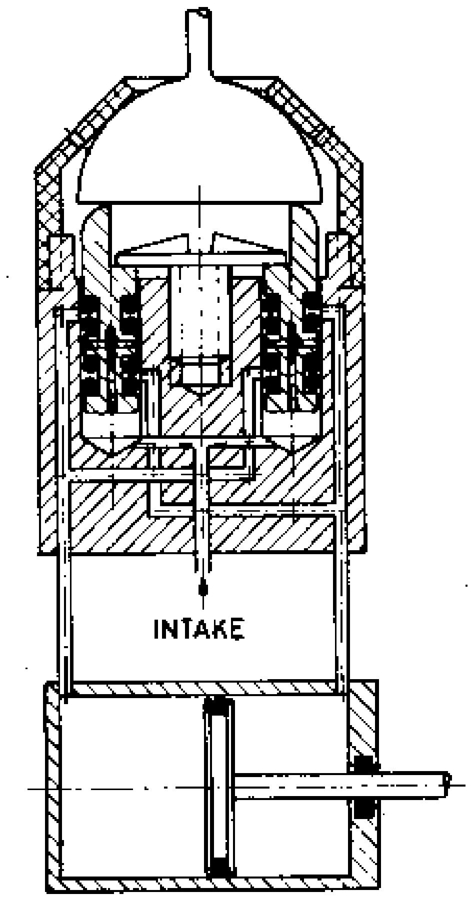


Figure 3. NBI four-way valve

At this position the actuator is connected to the supply pressure which is shown as + in the figure. When the joy-stick is gradually moved you start restricting the flow from the supply to the actuator, the point »O«, where there is no flow in any direction, is reached, and continuous moving of the joy-stick and plunger gradually exhausts the actuator, which is shown as — in the figure.

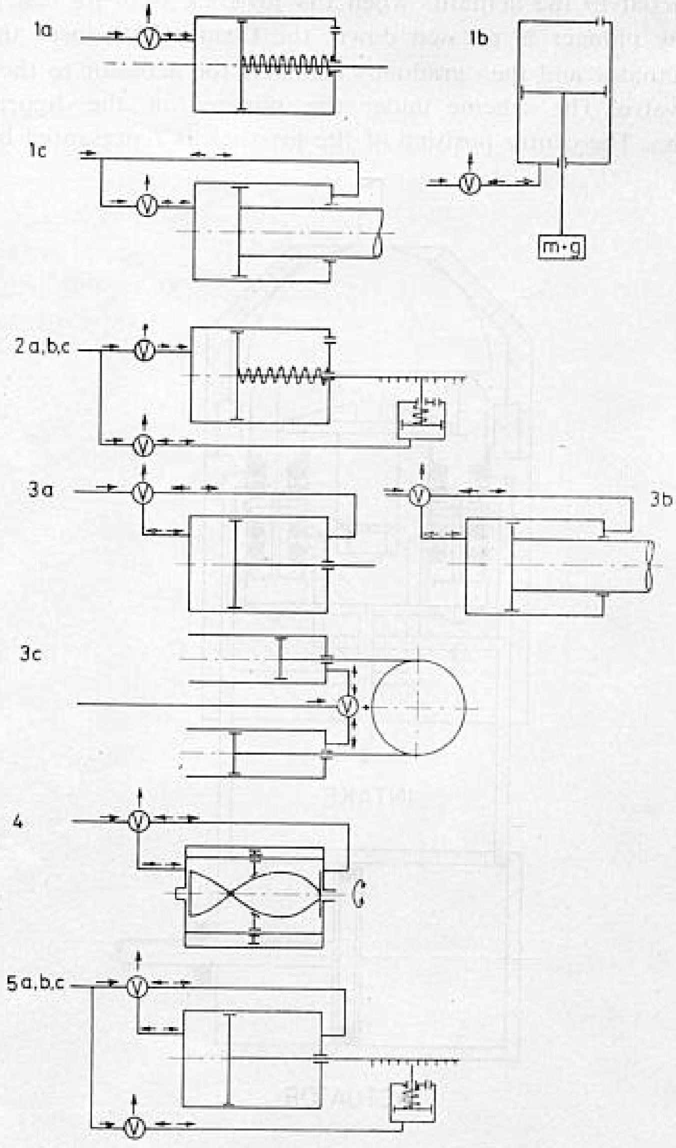


Figure 4. Actuators (pneumatic)

Plunger A will control the single-acting actuator with spring, gravity or constant pressure pneumatic return if you accept that there will be full pressure on the actuator when the joy-stick is at rest. This seems to be meaningful for some applications of pneumatic hooks or hands which then are closed at rest, provided that they are designed for active closing. Plunger A is also used for a single-acting actuator with pneumatic lock, where another plunger of the same type is used for the lock. The two plungers then have to be positioned 90 deg. from each other in the valve body. If the joy-stick is at origo there will be full pressure on the actuator but also on the lock. Movements of the actuator have to be effected with the joy-stick outside the »O«-position of the locking plunger in the quadrant between the lock plunger and the actuator plunger. This principle is used in our application of the Otto Bock elbow unit. The use is easiest to follow in Figure 6a, where direction right represents the lock and direction down represents the actuator. The two main disadvantages with this control are that the elbow cannot be coordinated with any other movement controlled by the same valve, and that the elbow cannot be unlocked with full pressure on the actuator. Though this is a safety advantage, it introduces a delay in the order of one second until the pressure in the actuator balances the forces which try to extend the elbow. The patient, however, learns how to control this very rapidly.

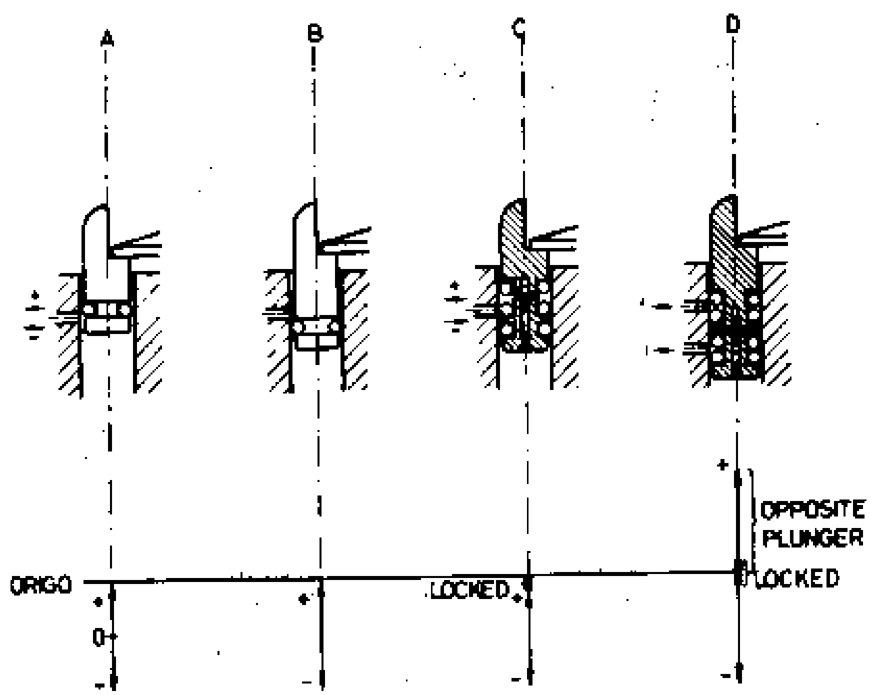


Figure 5. Basic plungers

Plunger A can also be used to control the double-acting, self-braking or externally locked actuator. A unit that can be made self-braking is the helical-screw actuator, modified for prosthetic use by

Dr E. A. Kiessling, American Institute for Prosthetic Research, New York. In such cases the plungers are arranged in a pair analogous to Figure 1 with one plunger connected to each side of the actuator, so that both sides are connected to the supply. Moving of the actuator now is effected by pressing down one of the plungers, which will exhaust one of the sides of the actuator. This is used for elbow flexion in Figure 6c. If the actuator is not self-braking but pneumatically locked, a third plunger can be used for the lock as described above.

Plunger B (Fig. 5) is a nonactive plunger, only serving the purpose of centering the joy-stick and sealing the hole, if not all four holes in the valve are used.

Plunger C at Figure 5 works as follows. The figure shows the rest position, where the outlet to the actuator is connected neither to the supply nor to the exhaust. The actuator then is pneumatically locked. There is a connection from the bottom of the plunger, which allows the gas to pass between the two upper O-rings. When the plunger is pressed down, the actuator is connected to the supply-pressure when the orifice is between the upper O-rings, and exhausted when the orifice is above the upper ring. Plunger C originally was designed to work together with the Otto Bock wrist turner or similar acuators, but it also controls very well the differential cylinder, which is a double-acting cylinder with a thick piston rod so that the upper face of the piston is bigger (usually twice as big) than the lower. If the lower side is directly connected to the supply, the actuator can be controlled in both directions by a valve connected to the upper side. Then this actuator from a control point of view is similar to a single-acting one with spring or gravity return.

The advantage of plunger C compared to plunger A, of course, is that the actuator can be stopped in any position and left there when another plunger is used.

Plunger D (Fig. 5) is designed for double-acting, not self-braking actuators and works in pairs in two opposite holes. It shows a little of the difference between the Hendon valve and the NBI system. If the plungers in Figure 1 are adjusted, so that the O-rings cover the outlets, the actuator will be pneumatically locked at rest. If now the lever is moved, one plunger goes up and the other goes down, which means that the pressure increases in one chamber in the actuator and decreases in the other chamber. However, as is clear from Figure 2, it is not, with similar adjustment of the NBI valves, possible to get supply-pressure into the actuator unless the centre-screw is taken away, and then self-centering of the joy-stick is sacrificed.

Plunger D gives locking capacity and self-centering when working in a valve body as in Figure 3 where the upper outlet from one of the plunger-holes is connected to the lower outlet from the opposite plunger. In the rest position of the joy-stick the actuator is locked pneumatically (it works as a pneumatic spring) because of the twin O-rings covering the orifices. As a plunger is pressed down it simultaneously connects one side of the actuator to the supply and the other side to the exhaust, and the actuator moves. Opposite direction is controlled by the opposite plunger. Figure 5D shows a pair of opposite plungers and as you see the actuator is locked when the joy-stick is close to the centre position. The distance from origo to the point where the actuator starts is adjusted by the centre screw.

Experiments have been done with a valve body as in Figure 2, but supplied with one-way valves in the bottom of each plunger hole, preventing gas from passing from the plunger to the supply or to other plungers. In such a body, plunger A will control movements of the actuator and the one-way valves will lock it. This gives a very stable control but requires rather high gas consumption.

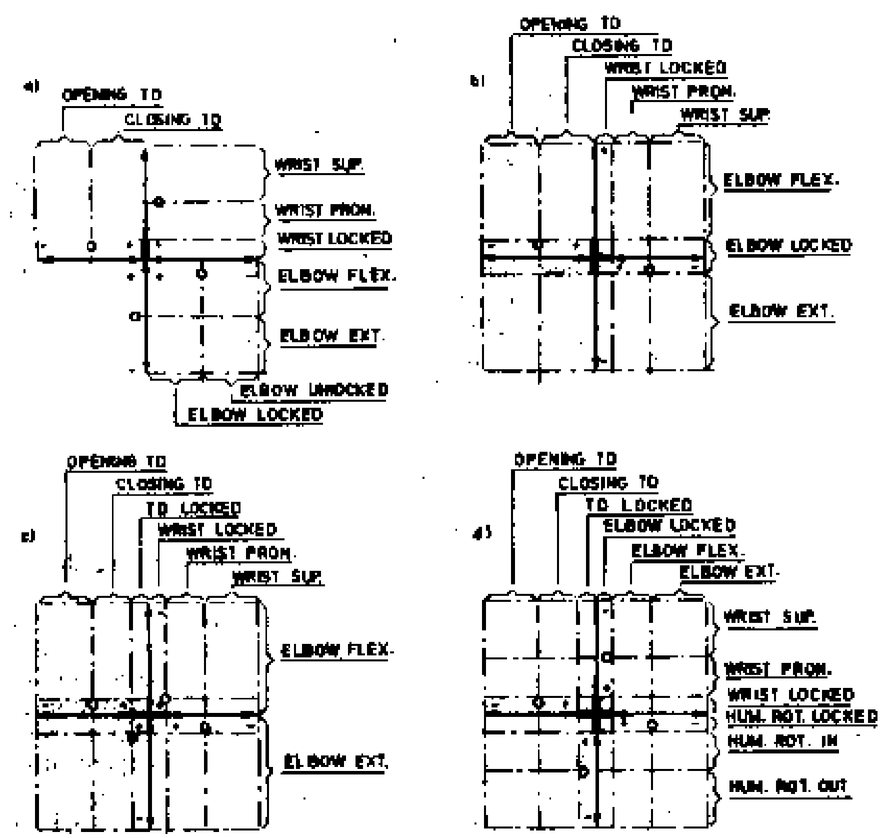


Figure 6. Application of NBI four-way valve for amelics

Valve bodies for a single plunger have also been developed. These units have two actuator connections and they can work with any of the above desribed plungers (Figs. 31, 32).

The NBI plunger-valves are not designed to work in a more sophisticated, closed servosystem. Their lags and flow/stoke characteristics are not up to such applications. They have, however, a fairly proportional flow/stroke characteristic, which in fact enables the user of the prosthesis to get a satisfactory control of the speed of the actuators.

Figure 6 shows four ways to use the four-way units. In Figure 6a an application with a pneumatic single-acting spring-returned hook, a single-acting spring-returned wrist rotator or humerus rotator, and a single-acting elbow with pneumatic lock are controlled (Fig. 17). The joy-stick is connected to a little cap, attached to the tip of the scapula. When the tip is moved forward, the joy-stick moves to the left in the diagram, where the hook is controlled. Elevation of the scapular tip moves the joy-stick upwards in the diagram, giving wrist — or humeral rotation. Direction right in the diagram unlocks the elbow, and direction down activates the elbow.

In Figure 6b a double-acting elbow flexion unit is used. Hook control is as previous — direction up flexes the elbow and direction down extends the elbow. Direction right then takes care of wrist — or humeral rotation. The two main advantages of the principle in Figure 6b compared to the one in Figure 6a are that there is better response in the elbow control, and, most important, that elbow movement can be coordinated with wrist rotation, which appears to be very helpful when the amputee is eating.

Our limited experience shows, that the lack of a »positive« elbow lock is compensated satisfactorily by pneumatic braking, provided that it is easy to control the elbow at very low speeds, and that the actuator is working very smoothly.

Figure 6c shows further a strategy, where, as mentioned above, a self-braking, double-acting elbow is used. This kind of mechanism, however, has a disadvantage in the fact that self-braking or mechanical nonreversibility implies a mechanical rate of efficiency below 50 per cent. In Figure 6c the T.D. control has plunger C. The T.D. then can be left in any position. This makes it possible to limit the prehension force, which was asked for by an amelic girl who expressed her desire to be able to eat fragile cakes.

Figure 6d shows an application where four different actuators are controlled from one valve. From this diagram it is easy to understand how coordination is performed. The valve has a »basic« origo, which is the rest position of the joy-stick, and where no actuator is working. There are four »secondary« origos, one in each quadrant, from which the two surrounding directions can be controlled independently and simultaneously. It is then obvious that opposite plungers can not be coordinated. The actuators can only be cyclically coordinated in pairs. The choice of cycle then has to be subject to logical and clinical evaluation.

All kinds of noise from the prosthesis is annoying for the patient, and pneumatic valves appear to have a tendency for exhaust noise. In our four-way valves (Figs. 2 and 3), the exhausted gas first comes into a little chamber (surrounding the head of the centre screw), and after that it leaves the valve through four small holes. This chamber in combination with the small holes, forms a silencer. Though this silence has not yet been optimized, it has a considerable effect.

Position and Force Control

The plunger valves control the flow of the gas or the speed of the actuator. Information about the position of the prosthesis is given by visual feedback. After some exercise the patient is able to integrate the magnitude of the control signal (the speed of the actuator) and thus know how much he, for instance, is flexing his elbow.

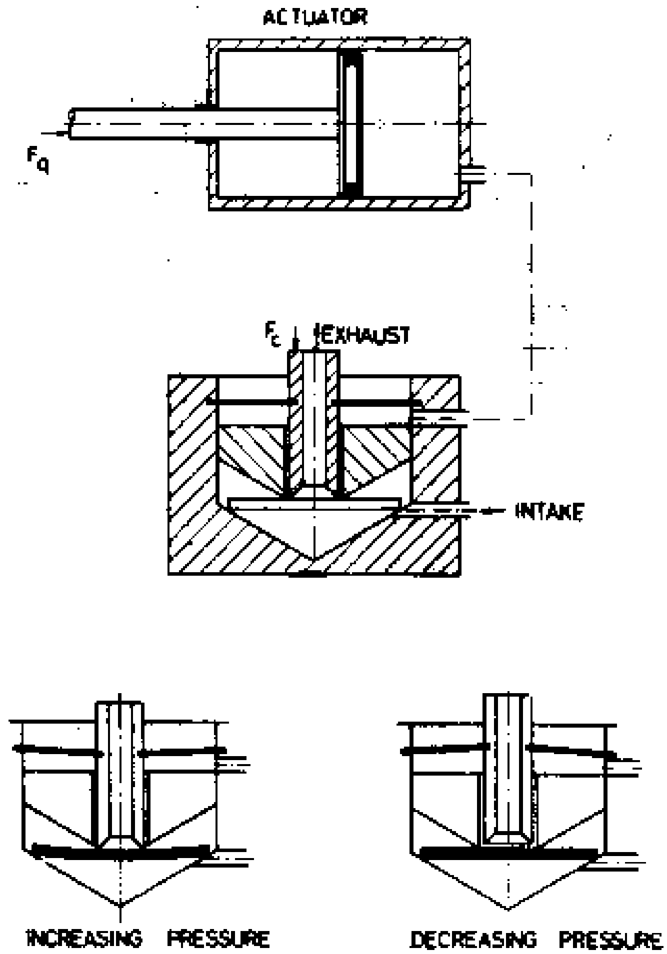


Figure 7. NBI pressure demand valve

If a double-acting actuator is used, position feedback can be obtained simply by mechanical connection between the actuator and the valve, so that the valve rotates as the actuator moves. If the valve rotates around the same axis as the joy-stick moves, and the feedback is negative, the actuator always stops in a position corresponding to the attitude of the joy-stick.

Perhaps more useful kind of feedback is the force feedback. Forces applied to the arm are usually fairly well transmitted through the socket, but the prehension force in the T.D. (hook or hand) is not known by the patient in current pneumatic systems.

This was, as we felt, a very severe drawback. Therefore we have developed a pressure demand valve (Figs. 7 and 18), originated by Mr. C-H Abrahamson, FOA. The valve has been simplified and considerably miniaturized. An early, too complicated four-way version of this valve (Fig. 19) was demonstrated at the »Conference on the Control of External Power in Upper Extremity Rehabilitation,« Warrenton, Virginia, USA April 1965.

The dimensions of the new prototype is 8 × 8 × 11 mm. The valve allows both speed and force control. The control stroke is less than ± 0.1 mm, and within that limit it gives a sufficiently linear stroke/flow characteristic. The control force always balances the pressure to the actuator.

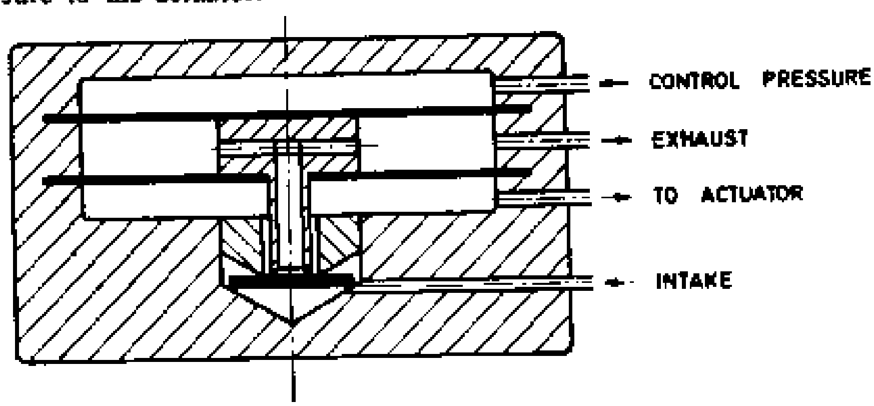


Figure 8. NBI pressure demand valve, second stage

In some clinical applications it might be advantageous to have a valve that can only increase pressure. It is then possible for the patient to hold an object without continually pressing the valve. In such cases another valve is necessary to decrease the prehension force and open the T.D.. The NBI pressure demand valve serves the first purpose, if it is made without the exhaust hole. The valve for decreasing the pressure is not critical, and can very well be an on/off valve.

The control force for 8 atm. output at 8 atm. supply pressure is for the prototype about 0.8 Kp. This force of course follows ϕ_2^2 (Fig. 9).

Some preliminary investigations on the possibility of solenoid control of this valve have been made by Mr. N. Ivančević, Mihailo Pupin Institute, Belgrade, when he spent three months with us recently. It worked but we would like to make use of a smaller solenoid. This is possible, if ϕ_2 (Fig. 9) is made smaller. But, as shown in Figure 9,

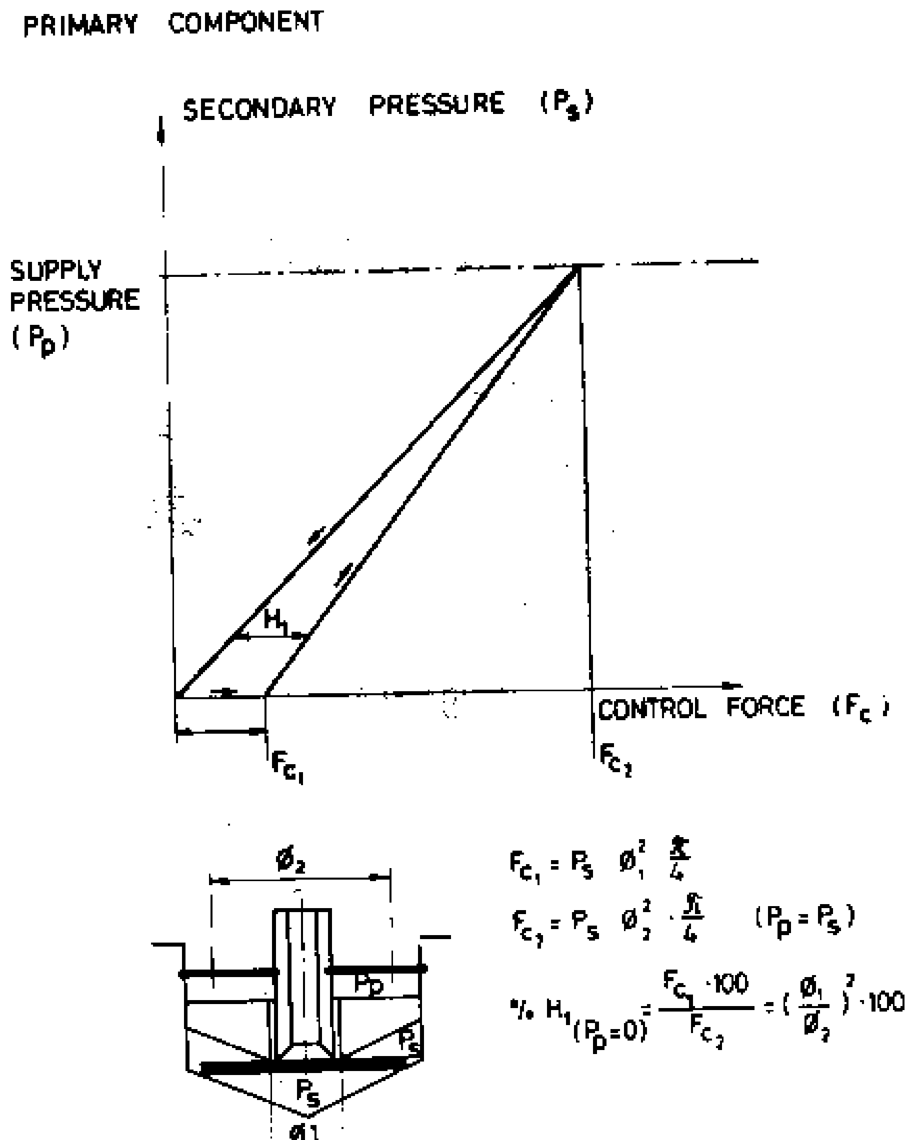


Figure 9. Hysteresis of NBI pressure demand valves

there is a hysteresis component depending on $\left(\frac{\Theta_1}{\Theta_2}\right)^2$. Thus it is also necessary to decrease ϕ_1. The solution of this problem may be a thin hypodermic needle with an outside diameter of less than 0.1 mm. But then the flow capacity of the valve will be too small to give sufficient speed to the actuator. Figure 8 shows a second stage for that purpose. This valve has pneumatic input, and is a simple pneumatic power amplifier.

The principle of the pressure demand valve has also been used in a pressure reducer for the gas container. This was an acute problem for us, as the well known Beacon pressure reducer is no longer available.

We want a pressure reducer, that gives a very stable supply pressure, with very little interference caused by the flow, in order to get reproducible control characteristics to the prosthetic system. Another desire is a safety device at the secondary side of the pressure reducer, to prevent bursting of the tubing. Thirdly, we want a smaller unit than the Beacon reducer.

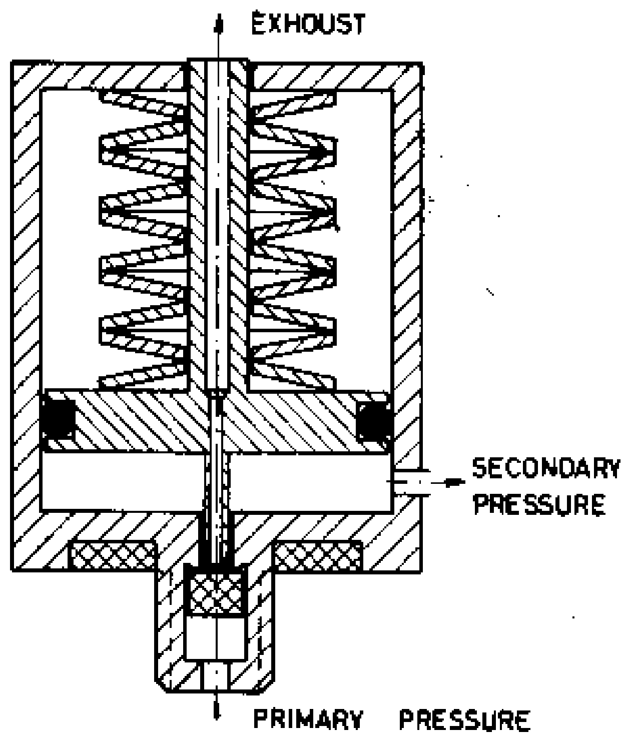


Figure 10. NBI pressure reducer

Figures 10 and 20 show the result. The accuracy of this valve is about $\pm$ 3% of nominal pressure. Use of the horizontal part of the characteristics of the Belleville springs (Fig. 11) provides minimum influence on the pressure from the flow. The outside diameter of the valve is 30 mm, and the length is 21 mm.

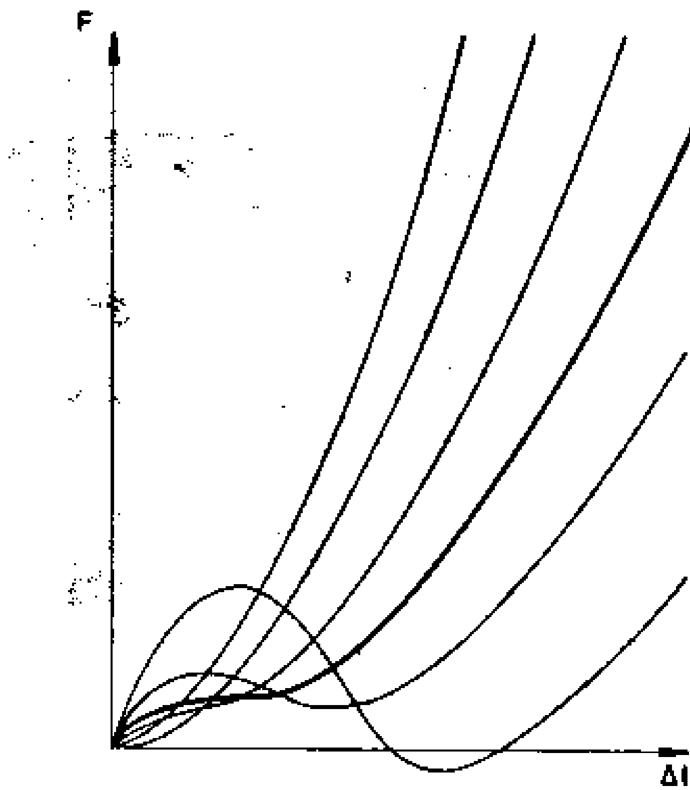


Figure 11. Characteristics of Belleville springs

Pneumatic Arms

When we started our work in February 1964, we only dealt with the control of pneumatic prostheses. Components for the arms were available from Otto Bock Orthopädische Industrie KG, Duderstadt, Germany (OB). For our first amelic application we used OB pneumatic hook, wrist turner and elbow on the right hand side, and on the left hand side we placed the wrist turner in the upper arm to get humeral rotation. To fix the arm to the plastic waistcoat, we made a 25 mm ball-joint which provided a passive, unlimited shoulder flexion-extension, and 45° shoulder abduction. The valve was mounted inside the ball (Fig. 21), with the joy-stick directed into the waistcoat, and connected to the little scapular cap (Fig. 22). (The idea of the scapular cap was given to us by Dr. Kiessling, when he spent a fortnight in Sweden in 1964. Considerable contributions to this technique have later been given by Dr. Winderlich.) In this first case the valve worked as in Figure 6a. The amelic cases are bilaterally supplied, and the main reason for the humeral rotation on the left side is that it allows some bimanual activities.

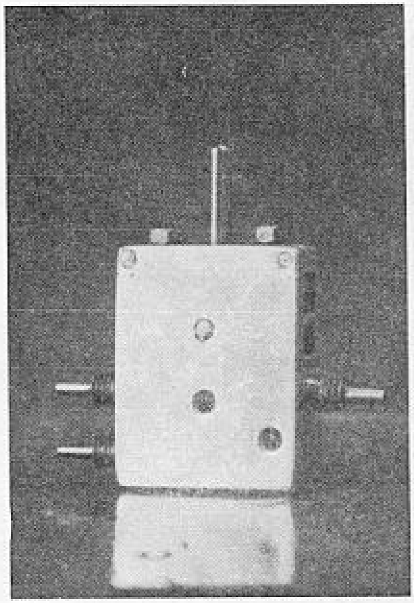


Figure 12.

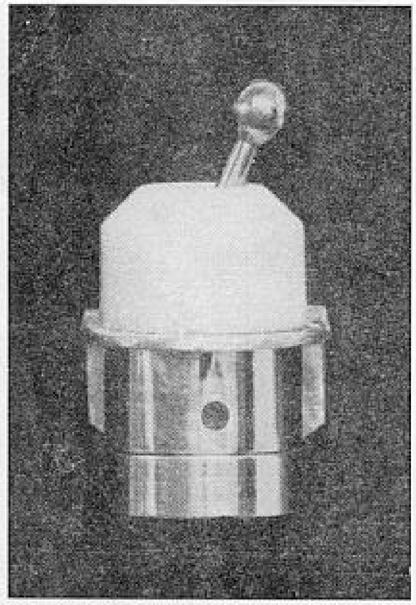


Figure 13.

For phocomelic cases we also want to achieve bimanual function. All phocomelic cases have one arm that is better than the other despite the fact that both generally are very bad, or, if the arms are equal,

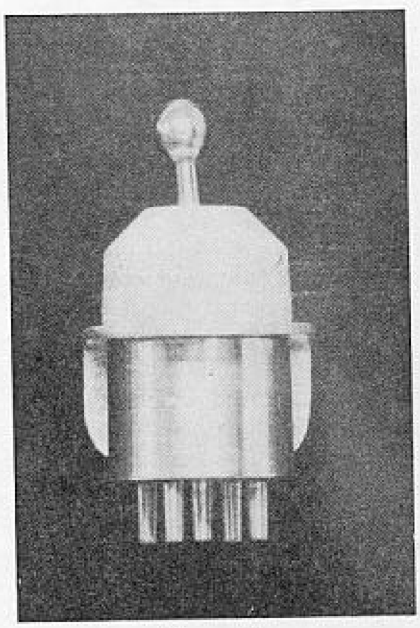


Figure 14.

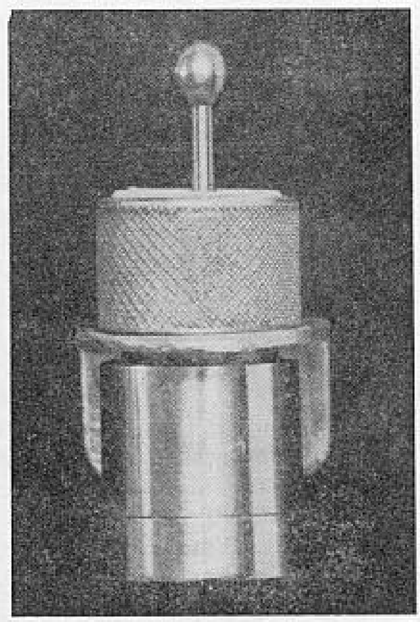


Figure 15.

one arm is dominant. We agreed in what, I think, was the general opinion amongst workers in this field, namely, that these cases should be supplied with an artificial arm on the worse side to work together with and serve the best natural arm. Then the best arm must not be involved in the control of the prosthesis. This, we felt, is the only way to take advantage from the sensory feedback of the natural hand, and still get bimanualism.

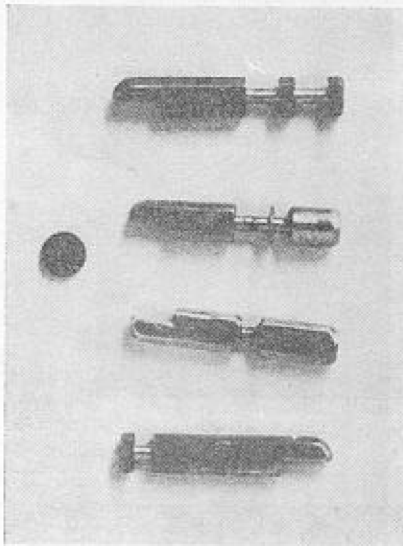


Figure 16.

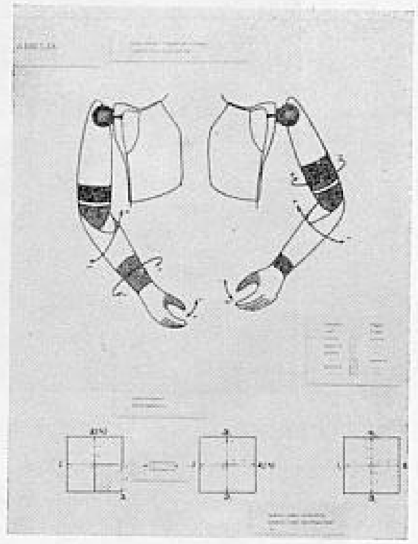


Figure 17.

We designed a very light arm (Fig. 23) with a double-acting cylinder for elbow flexion and connection for a pneumatic hook. For the shoulder joint we used a little ball joint, developed at Annastift, Hannover, Germany, and manufactured by OB. A valve was attached

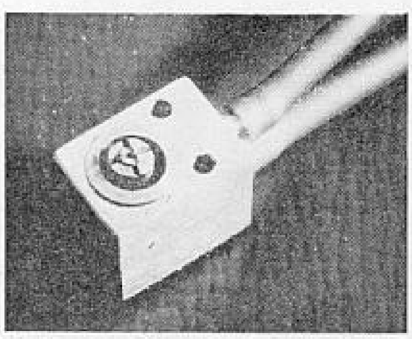


Figure 18.

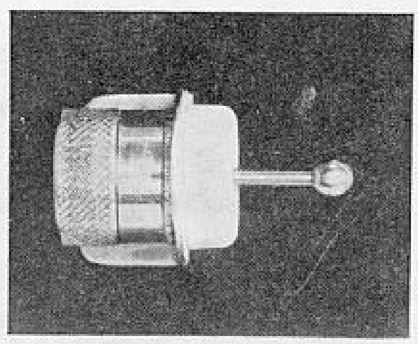


Figure 19.

to the waistcoat, so that it could be easily controlled by the natural hand (Fig. 24). We used the principle shown in Figure 6b, but as we had no active wrist rotation, we had a blind plunger (Fig. 5 B) in the unoccupied direction.

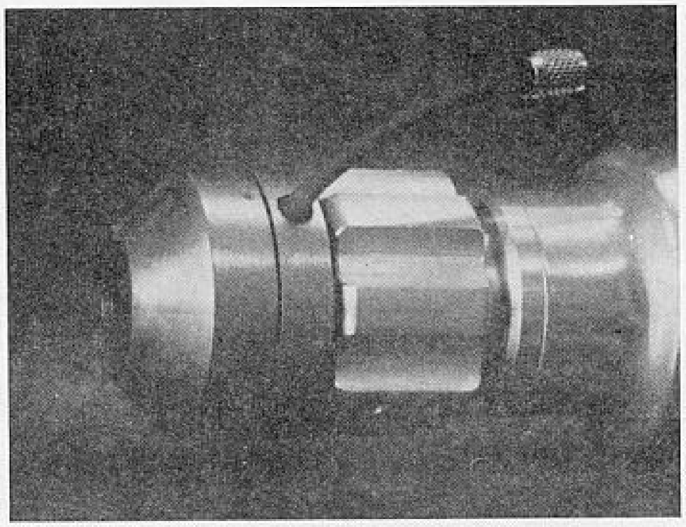


Figure 20.

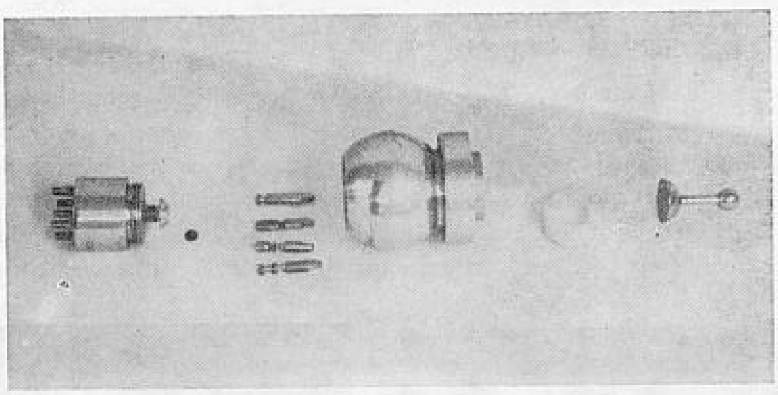
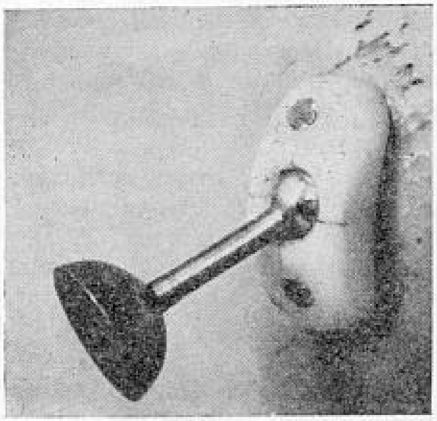


Figure 21.

I think that this application corresponded very well to what was made in other centres around the world at that time (1964). Our main objection against it was, however, that the range of action of the arm was too limited. The centrum of action was the elbow joint, which is too distal. We discussed different kinds of so called vector arms, moving from the shoulder joint, but the design and control problems of a shoulder with three degrees of freedom were too difficult to solve within a reasonable time.



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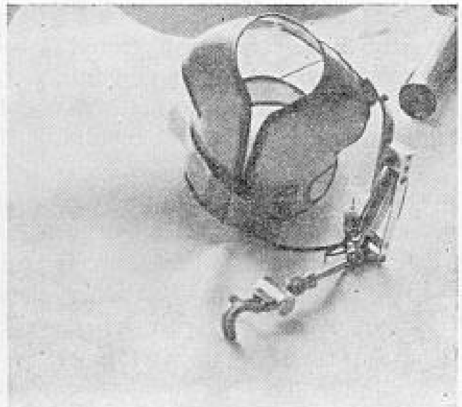

Figure 23.

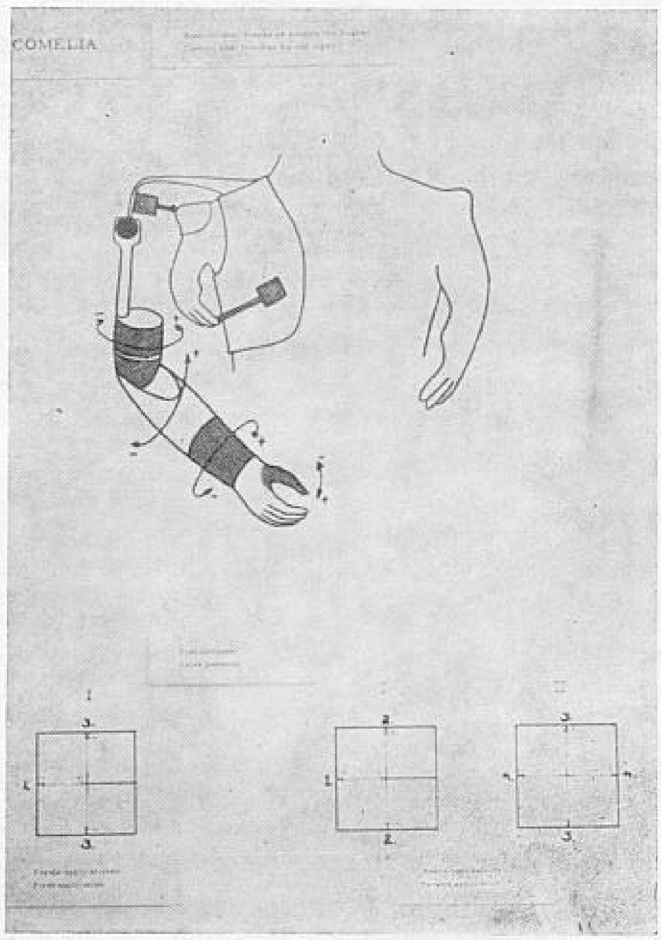

Figure 24.

A solution was given by one of the members of the SVEN-group, Stig Enger, who suggested a non-axial shoulder joint with a new geometry. I wil not run into details on this joint, as it will soon be published as part of a more comprehensive work by the originator. However, the clinical results of this joint are very promising.

One of the consequences of this joint is that the natural arm can move together with the upper arm of the prosthesis. The hand can still be used as a control site, but now the valves must be placed in the upper arm. Then there is to little room for actuators in the upper arm, and, despite the increased moment of inertia, we had to design a new lower arm with actuators for elbow flexion and wrist rotation.

This lower arm (Fig. 25) has pneumatic elbow with a differential cylinder. The big area of the piston flexes the elbow, and the small one is for extension. If it is controlled as a double-acting cylinder, it delivers about twice as much force for flexion as for extension. If it is controlled as a single-acting cylinder, the forces for extension and for flexion are equal. The wrist rotation too has a differential cylinder, and the rotation axis diverges 30 deg. from the long axis of the lower arm. There is also a passive rotation with adjustable disc-brakes around the long axis. As T.D. we use the OB pneumatic hooks. An joints in the arm have ball bearings, and the seals in the cylinders consist of rubber O-rings for elasticity covered by teflon rings for low friction.

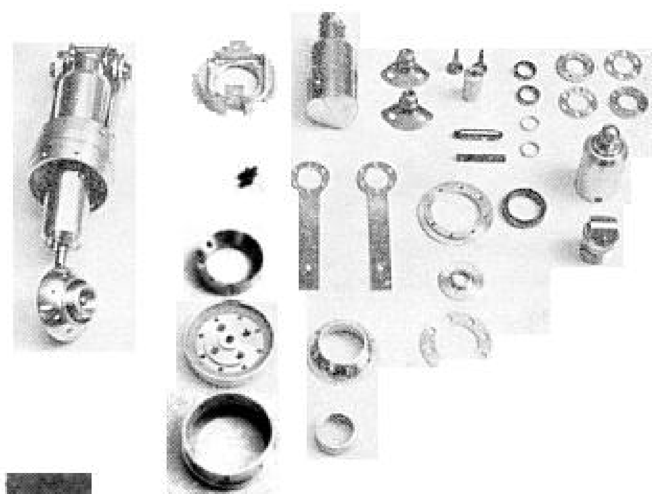

Figure 25.

We are now using this arm also for amelics, still with the passive ball joint in the shoulder and an OB wrist turner for humeral rotation. (Figs. 26—28). The valve arrangement for this application is shown in

Figure 6d. The patient can now get 8 pneumatic degrees of freedom (16 functions by the anatomical vocabulary), 4 on each side. The weight of each arm is less than 700 grams.

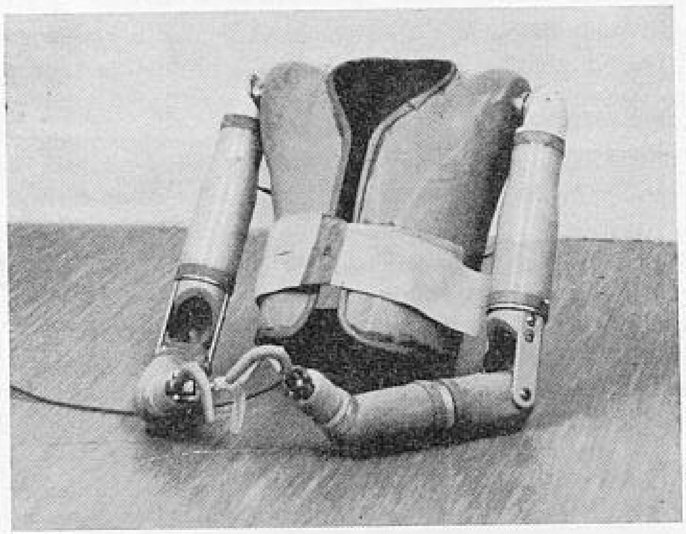

Figure 26.

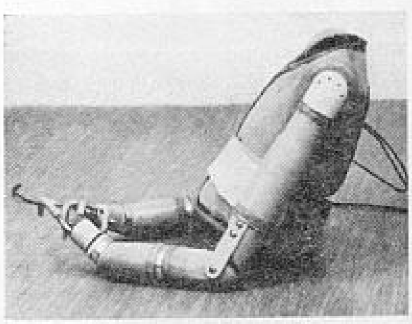

Figure 27.

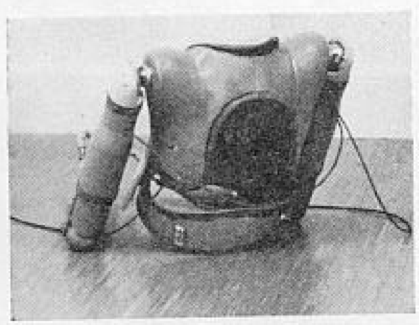

Figure 28.

As the children can be frightened when you put powerful prostheses with many functions on their bodies, we have made a »toy-arm« (Fig. 29), which can be controlled in the same way as they later will control their own prostheses. In this way the patients thus get a first conveniently distant confrontation to the pneumatic system. The toy-arm was suggested by one of our physicians, and I strongly believe that this way of introducing the complete system gives good results much faster than starting with one function at the patient and then slowly adding the others.

Sockets

Allthough I realize that this does not really belong to the subject of this Symposium, I would like to mention a few words about our work on sockets or waistcoats for artificial arms.

It is vitally important that the socket give a stable connection between the body and the prosthesis, and it is not less important that this connection is comfortable in any climate and under any condition. I will not say that these problems have been solved, and I do not believe that functionally really good results ever will be achieved by further development of sockets. The ultimate solution obviously must be direct fixation to the skeleton of the patient, but we all know that this is not medically possible yet. Thus we still have to try to make better and better sockets. Our work on this subject is in the hands of Dr. Winderlich, who is an experienced dentist. He has developed a new way to make porous sockets from epoxy (Fig. 30), and he has also made further development on the »stola-socket«, which is a torso socket originated at Orthopädische Universitätsklinik, Münster.

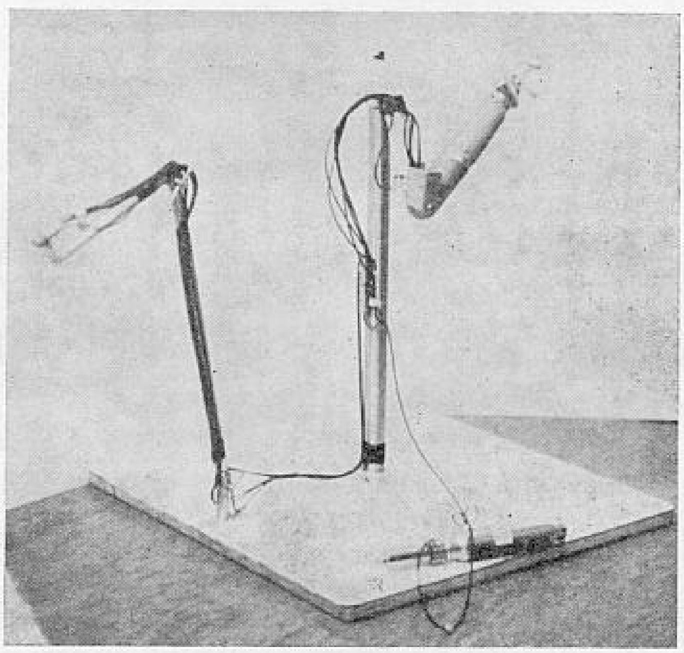

Figure 29.

Our way of picking up movements from the scapular tip at amelic and shoulder disarticulated cases calls for very accurate castings, and here Dr. Winderlich has converted the alginate technique, used by the dentists, to suit purpose. Unfortunately it is not yet possible to apply directed forces on the subject when casting, so there is further development on the method to be done.

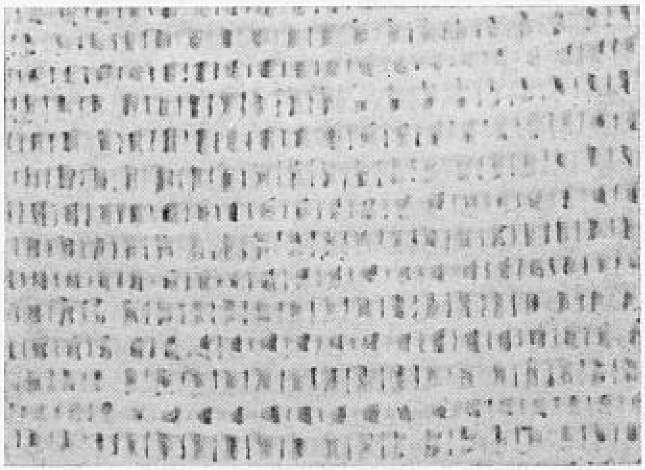

Figure 30.

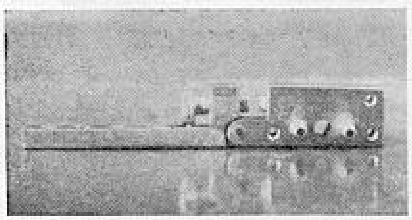

Figure 31.

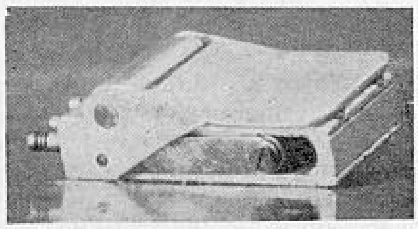

Figure 32.

More will be said about these questions next week in Münster. Just let me repeat what has been said several times: Any application of advanced, externally powered prostheses will fail if the fitting is not up to the same level.