Hydraulics for Prosthetic Devices

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One might commence with a paper of this title by reeling off a list of desirable attributes normally associated with the application of hydraulics. Diversionary logic such as a reminder that you stake your life on the side of hydraulics (i.e. brakes on your automobile) or to envisage for you the power associated with hydraulics (i.e. the garage lift that seemingly effortlessly raises your auto on a single steel finger) are arguments that may be irrelevant for the application that you contemplate. Obviously if one wishes to decide which is the optimum design between two prosthetic devices he must have considerably more information than just the engineering performance specifications. One must know the total demand, today, for a device—and prognosticate the demand for tomorrow. One must separate need from desire—must consider these as a function of cost—must relate these to the overall economy of a State or the Nation. These facets should be the topic for consideration sometime. But for now let us consider the application of hydraulics to a couple of "breadboard" models.

Fig. 1 illustrates a body-powered unit that employs hydraulic fluid for transmitting a simple figure eight harness to a Dorrance 5X terminal device. It is the hydraulic equivalent to the conventional Bowden cable system. The master cylinder I.D. (inside diameter) is 9/16"; the terminal device actuating cylinder I.D. is 7/16". The volumetric capacity of a cylinder is proportional to the square of its diameter. For the unit of **Fig. 1,** the ratio of the displacements of the master cylinder to the terminal

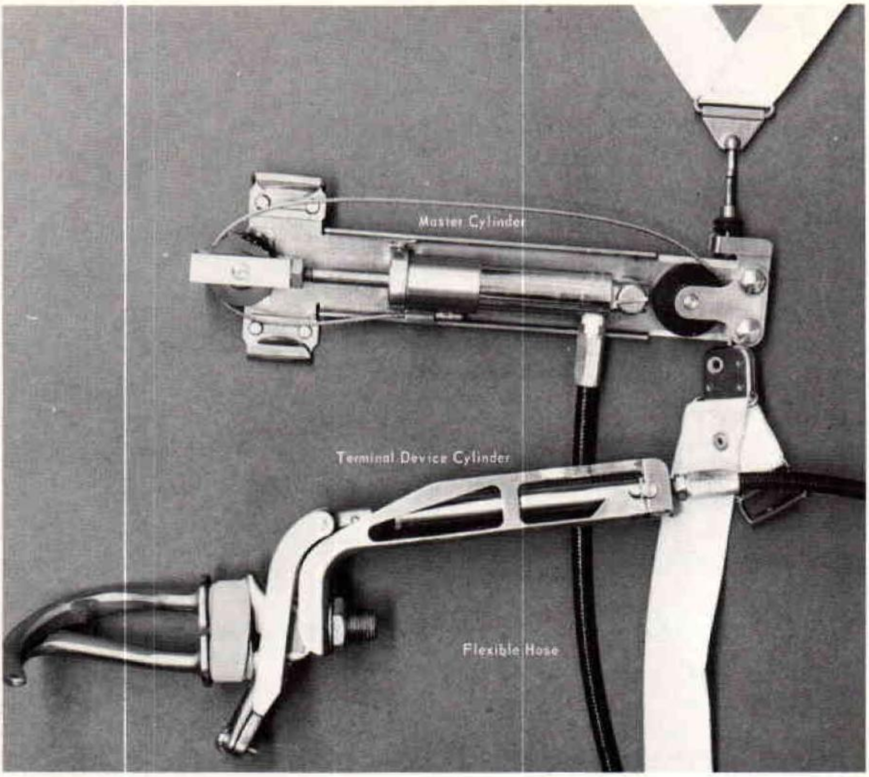

FIGURE 1—Body-Powered Hydraulically Operated Dorrance 5X Prosthesis.

cylinder equals $(7/16)^2 / (9/16)^2$ or 49/81. It was discovered in the first attempt to harness a small woman amputee that a better mechanical advantage was needed so the pulleys were added. This modification yields a ratio of displacement of the harness to displacement of the terminal device cylinder of 2 x 49/81 or 1.21. Preliminary experimental data indicates an overall system efficiency of approximately 80% when only 4 rubber bands are used on the terminal device. The system efficiency improves with increasing numbers of rubber bands as the seal friction in the hydraulic cylinders exists regardless of the number of rubber

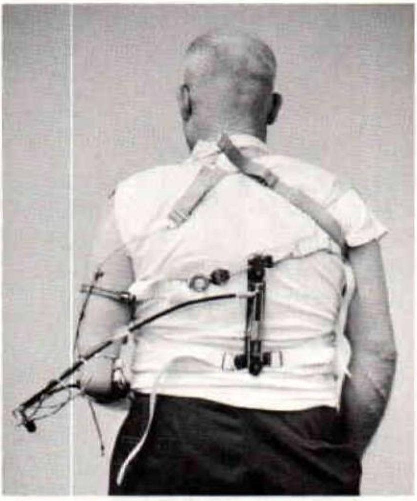

FIGURE 2—Body-Powered Master Cylinder and Bowden Cable Harness. Also, Transducer for Force Measurement.

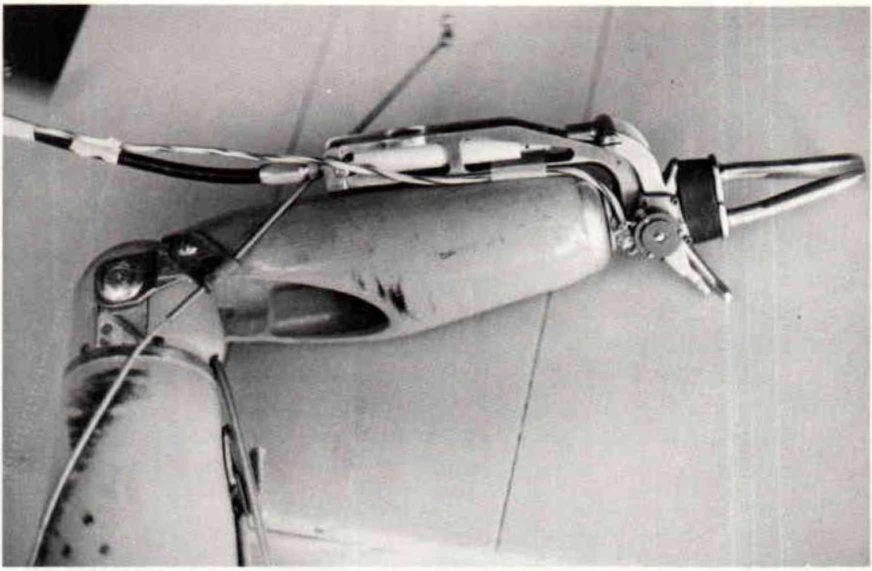

FIGURE 3—Body-Powered Terminal Cylinder, Bowden Cable Disconnected But Not Removed. Also, Transducer for Measuring Motion of Terminal Device.

bands on the terminal device. It may be worth commenting that the efficiency of the system is independent of the radius about which the flexible hydraulic tubing is bent. This same statement cannot be made regarding the Bowden cable system.

Some typical data related to the rubber bands on a Dorrance 5X terminal device are shown in **Table 1.** Due to the loose manufacturing tolerances maintained on the rubber bands, **Table 1** can be considered as representative only.

Table 1: Typical Data Related to Dorrance 5X Device.

No. of Rubber Bands	4	12
Max. Torque (inch-pounds)	30	110
Force on Lever at 1.875 inch (pounds)	16	59
Prehension at 4 inch Radius (pounds)	7	28

Considering the terminal device actuating cylinder with a cross-sectional area of 0.150 inch^2, the pressure required to overcome 12 rubber bands will be some 400 psi. The working pressure of the commercially available hose being used is 2500 psi with a burst pressure of 10,000 psi.

This information and experience to date suggests the trends for further work in the area of body-powered hydraulic devices. The sizes of the master and terminal cylinders will become smaller. This in turn will result in higher working pressures and increases in the overall system efficiencies. Harnessing for better utilization of the potential forces and excursions is presently being worked on. Minaturization of hydraulic components for orthotic and prosthetic applications brings its own problems—closer tolerances on sizes and finishes and greater care in assembly and maintenance. But miniaturization in hydraulics will come about—the question is whether or not the prosthetics and orthotics field will lead or follow in this transition.

Fig. 2 shows one initial attempt at harnessing an amputee with a body-powered hydraulically operated prosthesis. Some of the apparent complexity revealed in the photograph stems from the instrumentation of a force transducer as well as the harnessing used by the amputee for his Bowden cable.

Fig. 3 presents the terminal device actuator of the body-powered hydraulically operated system. The complicated looks are due, in part, to the instrumentation used for measuring the angular motion of the terminal device and the Bowden cable that was made inoperative but not removed from the prosthesis.

Electrohydraulic Unit

One can anticipate a need for orthotic and prosthetic devices that employ several forms of external power (i.e. other than body power). The system of **Fig. 4** illustrates one approach using hydraulic fluid as both a control and power transmission medium. The General Electric Company, as a subcontractor to the University of Virginia, deserves credit for work on this unit. This unit acts like power steering on an automobile.

With seven rubber bands on the terminal device of this electrohydraulic unit the application of about 3 pounds at the master actuator will initiate opening. By increasing the force at the master actuator, the terminal device will open farther. The terminal device will be completely opened with about 6 pounds applied to the master actuator. These force levels may be changed

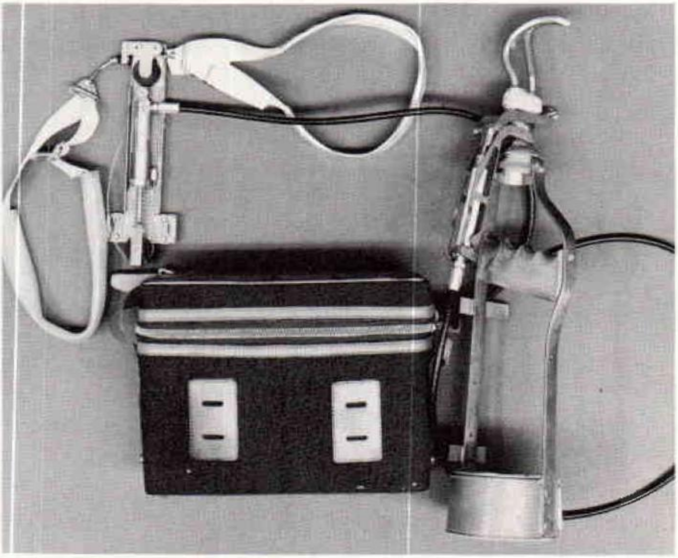

FIGURE 4—Electrohydraulic Power Assist System.

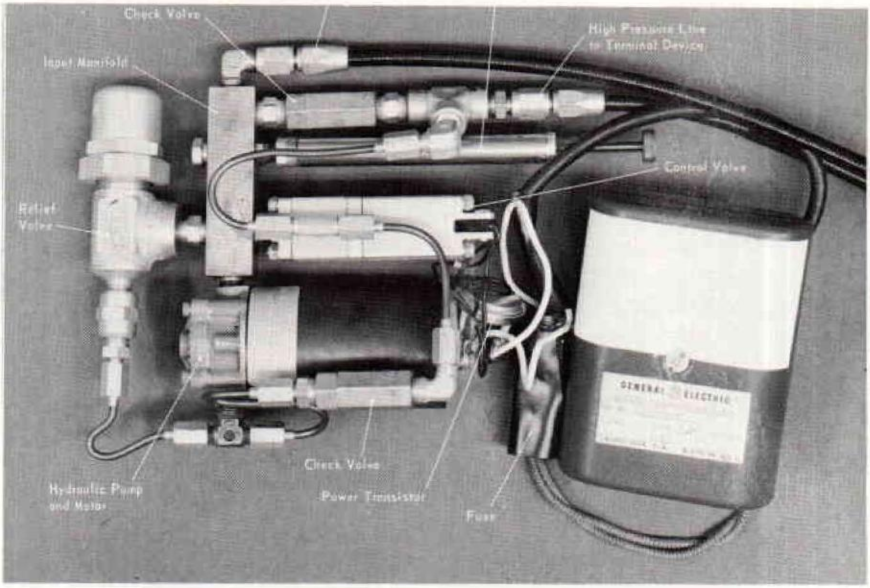

FIGURE 5—Details of Electrohydraulic Power Assist Unit.

by replacing springs in the control unit. One might anticipate using the prosthesis for light work (with few rubber bands on the terminal device) and not wish any external power assistance. At other times, a great deal more prehension might be called for and so also a need for power assistance.

Some of the details of the electrohydraulic power assist unit are shown in the photograph **(Fig. 5).** These details may be related as to function by considering the schematic diagram of the system of **Fig. 6.**

Operation of Electrohydraulic Unit

A description of the workings of this unit is best made by considering **Fig. 6.** A force applied to the master actuator (the cylinder that may be located on one's back) increases the pressure in the hydraulic fluid (Delco Supreme 550 hydraulic brake fluid). This pressure is transmitted to the terminal device actuating cylinder through the Control Valve. As the fluid pressure builds up, the Return Valve in the Control Valve closes. Then the path for fluid flow between the Master Cylinder and the Terminal Device is through the Check Valve. Increasing the force at the Master Cylinder will cause the spool within the Control Valve to displace farther and eventually reach a displacement that operates an electric micro-switch. When this happens, the electric motor is energized and through the hydraulic pump increases the pressure and fluid flow to the terminal device.

With the electric motor running, it is necessary to continue applying force to the Master Cylinder. If one stops displacing the Master Cylinder, that is if one does not maintain a force on the cylinder, the fluid pressure in this cylinder drops. This in turn means a drop of pressure in the Control Valve which is followed by motion of the spool within the Control Valve and this turns off the electric motor.

In order to close the Terminal Device, the force on the Master Cylinder must be decreased. Thus there is a range of force on the Master Cylinder over which no motion of the Terminal Device takes place. This means that a user can take less precaution in his overall actions and not cause either opening or closing of the device. A continued decreasing of force on the Master Cylinder will eventually allow the cylinder within the Control Valve to move to the point where the Return Valve opens. The Terminal Device will close in proportion to the motion of the Master Cylinder.

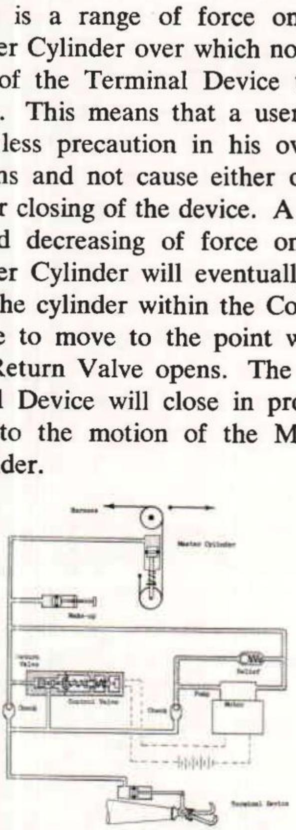

FIGURE 6—Schematic Diagram of Electrohydraulic Power Assist System.

For the case of no external power —i.e. the battery goes dead or is disconnected — everything happens as before except that the motor is not energized. Then the fluid from the Master Cylinder passes through the Check Valve toward the Terminal Device and behaves just like the body-powered hydraulic system. In short, it is a fail safe system that may be operated (if one has sufficient strength) with or without the power assist feature.

Summary

Breadboard models of the body-powered and electrohydraulic systems have been constructed. Some problems of the man-machine interface have been solved. Further input data on this interface problem is needed—data which you might be in a position to provide.

Hydraulics for orthotic applications seem to be a natural follow-on. To the present we have made no attempts to apply electrohydraulic systems in this area although we have considered the needs with patients.

Harnessing efforts are presently being pursued. Miniaturization of the systems are being considered. Hydraulic systems with different types of control and response characteristics are in order before the "best" scheme can be selected. Further testing will be required and then the manufacture of several prototypes will be in order.

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