Current Evaluation of Hydraulics to Replace the Cable Force Transmission System for Body-Powered Upper-Limb Prostheses

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Assist Technol 1990;2:101–107

Current Evaluation of Hydraulics to Replace the Cable Force Transmission System for Body-Powered Upper-Limb Prostheses

Maurice LeBlanc, M.S.M.E., C.P.

Rehabilitation Engineering Center, Children's Hospital at Stanford

Present body-powered upper-limb prostheses use a cable control system employing World War II aircraft technology to transmit force from the body to the prosthesis for operation. The cable and associated hardware are located outside the prosthesis. Because individuals with arm amputations want prostheses that are natural looking with a smooth, soft outer surface, a design and development project was undertaken to replace the cable system with hydraulics located inside the prosthesis. Three different hydraulic transmission systems were built for evaluation, and other possibilities were explored. Results indicate that a hydraulic force transmission system remains an unmet challenge as a practical replacement for the cable system. The author was unable to develop a hydraulic system that meets the necessary dynamic requirements and is acceptable in size and appearance.

Key Words: Prosthesis — Upper-limb — Arm — Body-powered — Cable control.

Body-Powered vs. Externally Powered Prostheses

Present body-powered upper-limb prostheses are not aesthetically pleasing; see, for example, Fig. 1 and 2. Individuals with arm amputations desire prostheses that are natural looking and are smooth and soft on the outside (1). There are two kinds of arm prostheses in use. The standard or conventional type is body-powered and uses a shoulder harness and a cable to couple shoulder "shrugging" to prosthesis operation. The other type is battery-powered, with a motor operating the prosthesis in response to electromyographic (EMG) signals or control-switch closures.

Standard body-powered upper-limb prostheses have not changed significantly since developments in the 1950s spurred by World War II. The steel cables they use for operation were adapted from aircraft technology. If one looks at the *Manual of Upper Extremity Prosthetics* (1952) or the *Orthopaedic Appliances Atlas* (1960) and compares these with the 1991 state of the art, one will not find a great deal of change.

Some individuals with arm amputations purchase electrically powered prostheses because they look more modern, high-tech, or "bionic." My observations suggest that the primary benefit of externally powered arm prostheses is not the external power feature per se but rather the comfort from reduced harnessing and improved cosmesis that results from reduced external hardware. The primary disadvantages of present externally powered prostheses are cost, weight, and lack of sensory feedback. Also, externally powered prostheses are more complex, necessitate daily battery charging, and require above-average clinical competence to fabricate, fit, and maintain.

Because comfort and appearance are very important, more and more arm amputees are opting for externally powered prostheses (2). Body-powered prostheses generally are the more functional alternative if amputees have adequate body motion and strength for control, but they simply are not as appealing an alternative (3,4). Their appearance is poor, and the shoulder harnesses are uncomfortable, restrictive, and can cause compressed nerves

Address correspondence and reprint requests to Maurice LeBlanc, Rehabilitation Engineering Center, Children's Hospital at Stanford, 520 Sand Hill Rd., Palo Alto, California 94304, U.S.A.

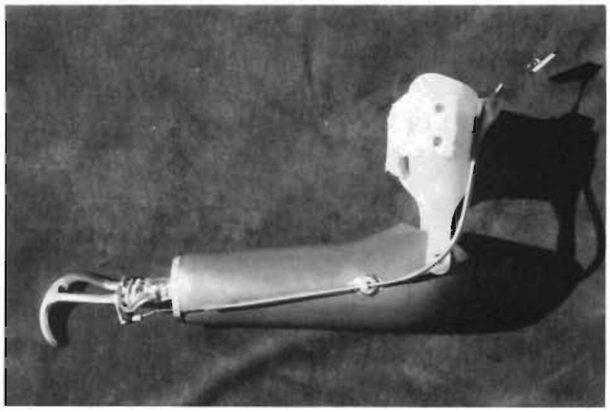

FIG. 1. Standard below-elbow (BE) prosthesis showing hook prehensor, socket, and triceps cuff.

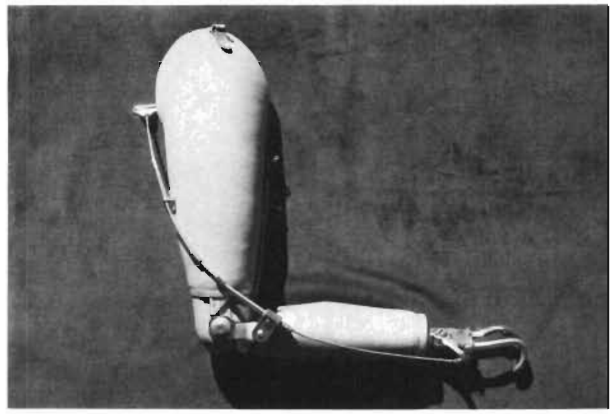

FIG. 2. Standard above-elbow (AE) prosthesis showing hook prehensor, forearm, and socket.

or reduced blood flow around the axilla. Although the basic purpose of external power is to provide assistance to amputees who lack the necessary body power, some amputees select externally powered prostheses for the improved comfort and appearance they do not get from body-powered prostheses.

There is a clinical place for both externally and body-powered arm prostheses. However, if body-powered systems could be improved in comfort and appearance, decisions on prescription and purchase could be made on a more functional and objective basis. Epps (5) states that much research remains to be done in upper-limb prosthetics, with cosmesis being a major concern. A United Kingdom survey, which included U.S.A. technology, identified artificial limb cosmesis as a research priority (6). Past (7) and recent (8) national workshops on prosthetics continue to recognize conventional upper-limb prosthetics as an area of high need. Burgess (9) has stated that

> . . . most upper-limb amputees still use body-powered prostheses. We aren't putting much research effort into improving these appliances, with the result that a majority of the upper-limb prostheses in use today are little changed from those fitted 15 to 20 years ago. A "re-visiting" of body powering, in the light of current technology, could yield great patient benefits.

Only 50% of arm amputees are estimated to wear prostheses, versus 75% for leg amputees (10). This difference is due in large part to the fact that people must have two legs to walk. It is also due to the very difficult task of making arm prostheses that function satisfactorily in three-dimensional space and look good to the public eye.

Target Population

Estimates place the number of upper-limb amputees in the U.S.A. at 100,000 (11). Of the estimated 50,000 arm amputees wearing prostheses, surveys of prosthetics facilities suggest the following levels of amputation: 58% below-elbow, 27% above-elbow, and 15% at hand/wrist or shoulder (10). Of prostheses being worn, estimates suggest that the percentage that are externally powered has increased from 5% to 10% in recent years (D. S. Childress, pers. comm.).

The population of interest here is the estimated 90% of 50,000 arm prosthesis wearers who are using body-powered systems. Also, some of the 10% who wear externally powered systems have standard body-powered prostheses for back-up or functional use. Thus the U.S. population of amputees with body-powered upper-limb prostheses numbers in excess of 45,000. Although the use of hydraulics would benefit all types of cable-operated prostheses, this project is focused at present on unilateral *below-elbow* prostheses because (a) this is the largest user group and (b) because below-elbow prostheses only require control of prehension (whereas above-elbow prostheses are two-degree-of-freedom devices).

With respect to age, most arm prosthesis wearers are either children with congenital amputations or working-age adults with amputations due to accidents. In terms of gender, most arm prosthesis wearers are male because of the preponderance of traumatic arm amputations resulting from accidents during typically male activities, in particular motorcycle riding, heavy equipment operation, power-line service, and other industrial occupations.

Advantages of Hydraulics

Efficiency

As demonstrated in a previous study (12), the standard cable-operated prosthesis has frictional

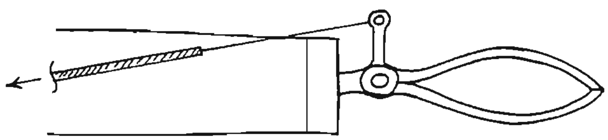

FIG. 3. Standard exoskeletal external-structure BE prosthesis with cable and hardware on exterior.

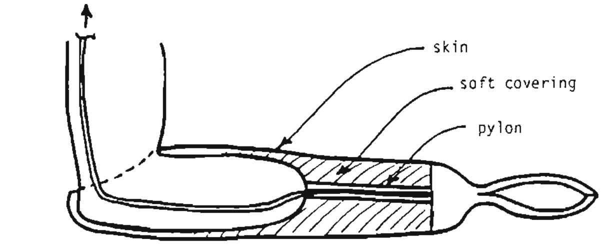

FIG. 4. Cutaway view showing endoskeletal internal structure with hydraulic line placed inside to allow soft, smooth exterior.

losses between the cable and its housing that increase with bending. For instance, at 180° of bend, the efficiency varies from 67% to 90%, depending upon the type of cable and housing. This means that between 33% and 10% of the work done at the harness has no external effect on prosthesis operation. At 360° of bend, the efficiency range is 10% to 80%. By contrast, a hydraulic system has small frictional losses in the piston seals of the cylinder but the efficiency stays constant over any angle of bend from 0° to 360°. In a breadboard system tested in the same study mentioned above, the efficiency of the hydraulic system with standard commercial cylinders was 90% over all angles of bend. Therefore, the hydraulic system has potential for improvement in efficiency with concomitant reduction in forces the amputee must exert for operation of the prosthesis.

Comfort

The harness itself is not uncomfortable. Instead, it is the force on the harness that causes the discomfort, particularly in the axilla or underarm area. Increasing the force transmission efficiency will help by reducing the force on the harness. For instance, if a 20-pound pull is necessary to operate the prehensor, the force required on the harness would be 40 pounds with a 50% efficient transmission system but only 22 pounds with 90% efficiency.

Appearance

Appearance is very important to individuals with arm amputations. Present cable-operated prostheses typically have the steel cable, housing, retainers, base plates, and other hardware all mounted on the exterior. This hardware is aesthetically unappealing, tears clothes and gets them dirty, and snags on objects. Also, the exterior surface of present prostheses is usually a hard, laminated plastic that slips on hard surfaces, resounds when bumped by hard objects, and is unpleasant to the touch. Hydraulics would allow implementation of an "endoskeletal" system in which the structural elements, the hydraulic line, and actuator are all placed inside the prosthesis and a soft covering and "skin" are placed externally to provide a more acceptable appearance and feel (see Figs. 3 and 4).

Prior Work

The author knows of four projects involving the use of hydraulics for transmission of body power to operate upper-limb prostheses: (a) IBM developed a hydraulic system operated by the foot (13). It was judged cumbersome and was abandoned. (b) All-American Engineering Co. in cooperation with Eugene duPont Memorial Hospital in Wilmington, Delaware, developed an all-nylon, compact hydraulic system for operation of a "Helping Hand" orthosis (14,15). However, this work was not continued. (c) At the University of Virginia in Charlottesville, a hydraulic system was developed for replacement of the upper-limb prosthesis cable system (16,17). This work was not continued. (d) Currently there is work being undertaken by Cool at the Delft University of Technology in the Netherlands. The results of this work are not yet published.

Although the use of hydraulics has been previously unsuccessful, the author concluded that it was feasible to attempt because (a) technology now exists to make "closed" hydraulic systems using rolling diaphrams or bellows that are less prone to leakage than "open" systems with O-rings, (b) previous efforts seemed to have stopped because of lack of funding rather than lack of confidence in hydraulics, and (c) more miniaturized hydraulic components are now available. Also, the author communicated personally with the researchers on three of the above projects and received encouragement to undertake new work.

Development of Three Prototypes

Because (a) hydraulics offered potential advantages in efficiency, comfort, and appearance over standard body-powered arm prostheses; (b) current technology made the application of hydraulics more

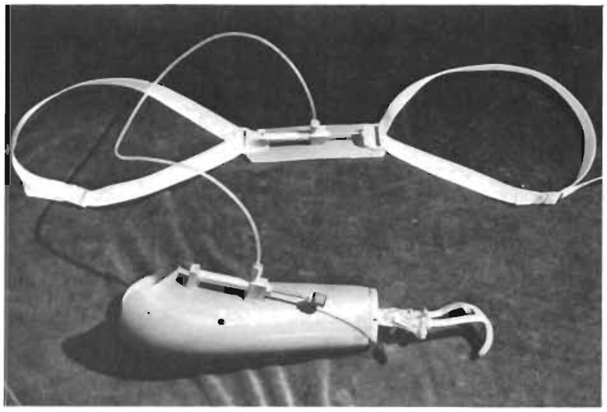

FIG. 5. Prototype control system with standard hydraulic cylinders located outside the prosthesis.

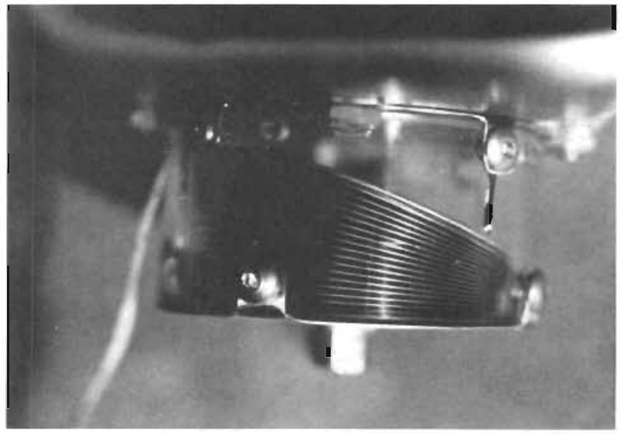

FIG. 7. Master bellows on triceps cuff expanded before compression by cable pull.

likely to succeed; and (c) there appeared to be no reasons from prior work that hydraulics could not be implemented successfully, the author undertook to design and develop a hydraulic force transmission system to replace the existing cable systems. Three prototypes were made.

Proof-of-Concept System

To test the idea and to get an understanding of the problems, a hydraulic control system was developed and placed on the exterior of a below-elbow prosthesis for evaluation (see Figs. 5 and 6). A master cylinder was placed in the harness on the amputee's back to generate force and excursion by scapular abductions in the usual manner. A slave cylinder was placed on the forearm to operate the prehensor. The slave cylinder mirrored the action of the master cylinder. The two cylinders were identical stock Clippard Minimatic brass components connected by clear vinyl tubing (1/8 in. outside diameter) with water as the working fluid. These stock cylinders were used because they were convenient for fitting and were readily available. They are not appropriate for clinical use because a 2-in. excursion would require 5 in. of length for the pistons, cylinders, and end adapters, making them too long for practical use.

Bellows System

Subsequent to the proof-of-concept system, a hydraulic control system was made for placement inside the prosthesis by using metal bellows (see Figs. 7–10). The master bellows on the triceps cuff was compressed by cable pull from the shoulder harness. The slave bellows connected by vinyl tubing then expanded to operate the prehensor. The stainless steel bellows were stock components from Metal Bellows Corporation and were chosen for their long life and low friction. The master bellows was

FIG. 6. Prototype control system with standard hydraulic cylinders fitted with harness.

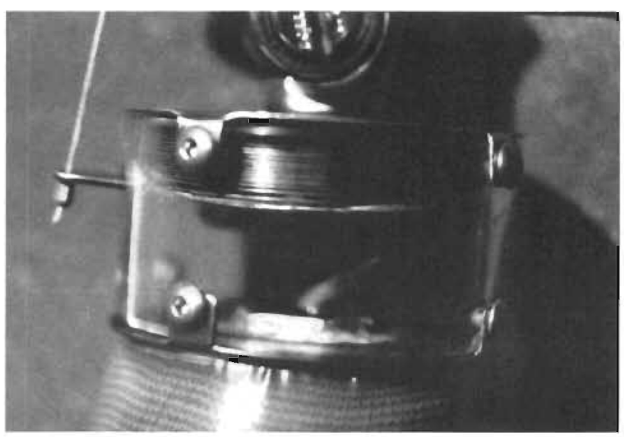

FIG. 8. Slave bellows on the wrist compressed before expansion and operation of the prehensor.

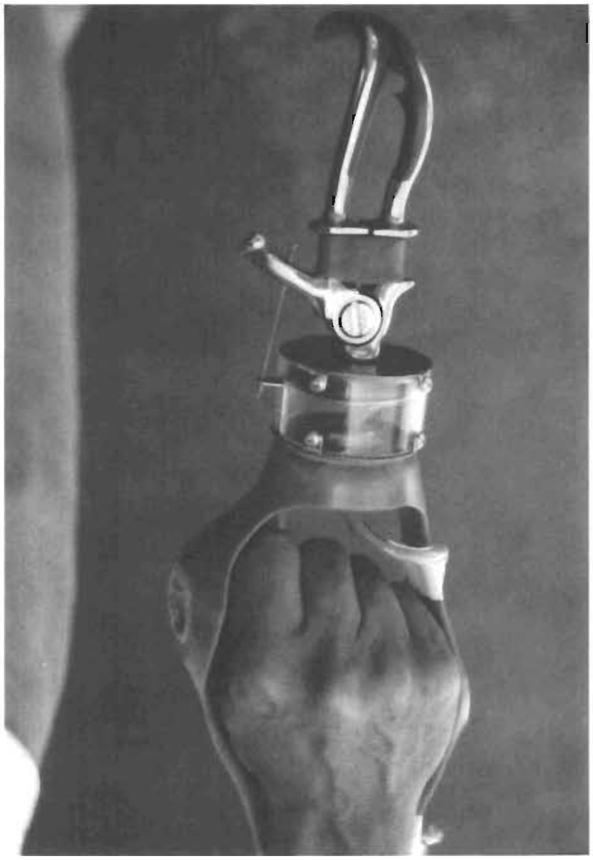

FIG. 9. Slave bellows mounted on experimental prosthesis.

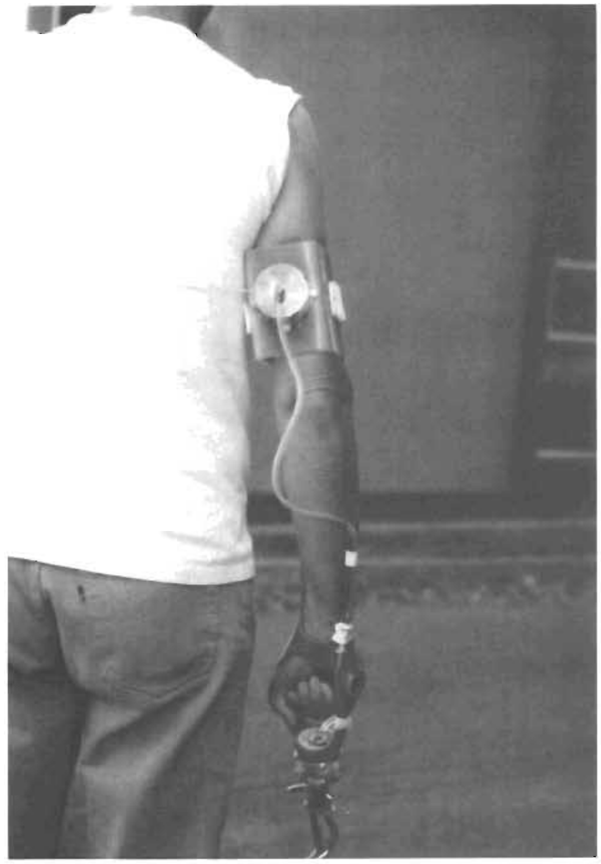

FIG. 10. Bellows system fitted to normal subject for laboratory evaluation.

placed on the triceps cuff because it can more easily be concealed under a sleeve there, and most below-elbow prostheses use tricep cuffs (see Fig. 1 for example).

Mathauser Hydraulic Brake System

William Mathauser (Anacortes, Washington) developed a hydraulic system to replace the brake cables on bicycles. It was selected for prosthesis activations because it has many of the design features desired for application in prosthetics. It is a closed system using rolling diaphram seals, braided wire–covered plastic tubing, and silicone fluid. It features low friction and quiet leak-free operation, and has a successful performance record. Mr. Mathauser made a special system with longer stroke for this project. It was incorporated into a prosthesis for laboratory evaluation (see Figs. 11–13). It incorporates a master cylinder on the triceps cuff and a slave cylinder in the wrist section. Both units were made from commercially available, oversized clear plastic cylinder stock to permit viewing the action of the system.

Evaluation of the Three Prototypes

Proof-of-Concept System

This external system was tested with six below-elbow amputees by fitting them with the harness

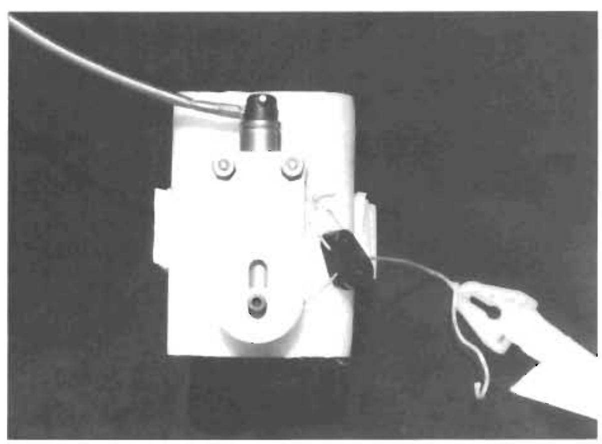

FIG. 11. Mathauser hydraulic brake master cylinder incorporated into triceps cuff with pulley to double the excursion.

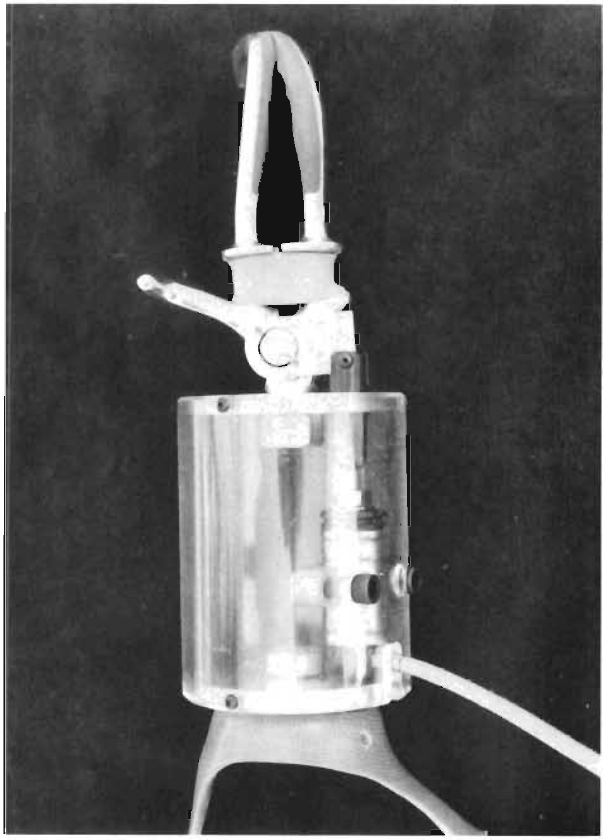

FIG. 12. Mathauser hydraulic brake slave cylinder incorporated into the wrist section with large, clear plastic housing to view its action.

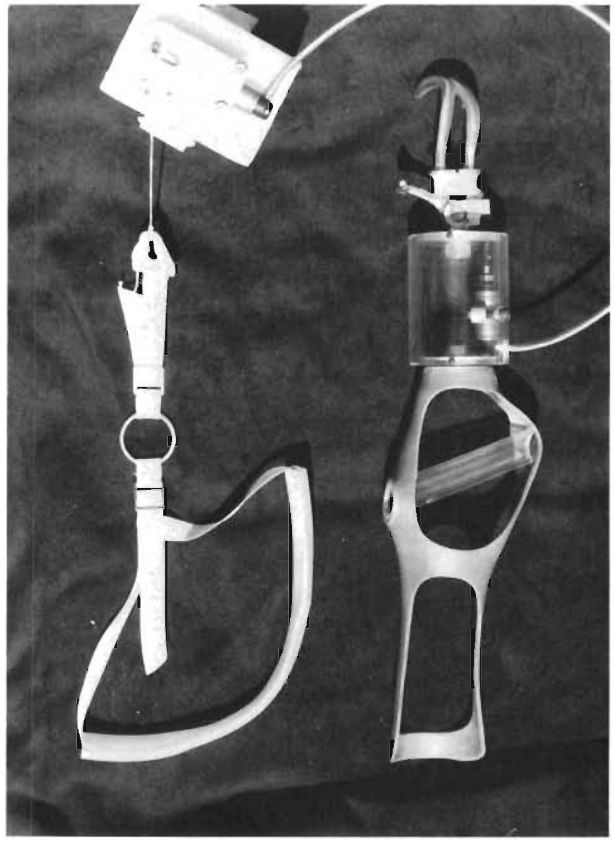

FIG. 13. Mathauser hydraulic brake system shown with experimental prosthesis for laboratory evaluation.

only as shown in Fig. 6 and having them actuate the prehensor. The subjective response was that the hydraulic control was quiet, felt smooth, worked easily, and had promise for functional use compared with their own prostheses. With this assurance, design and development of a hydraulic system to be placed internally in the prosthesis were initiated.

Bellows System

This system (Fig. 10) was demonstrated to professionals at the Sixth World Congress of the International Society for Prosthetics and Orthotics and at an Advisory Group meeting for this project. Consensus of these professionals and evaluation by the author determined that the system worked effectively but was unsatisfactory because the master bellows, or "body pump," cannot be enclosed in a sufficiently small package on the triceps cuff. The difficulty lies in accommodating the large excursion of body motion in a small space. This problem does not exist with the slave bellows because the excursion and force can be changed to suit the space requirements. An adult can generate 2 in. excursion and 60 pounds force by scapular abduction, and these figures become the specifications for the transmission system.

Mathauser Hydraulic Brake System

This system (Fig. 13) was demonstrated to professionals at an Advisory Group meeting for this project. Participants and the author concurred that it had the same difficulty as the bellows system. A master cylinder or body pump that met the necessary functional requirements of 2 in. excursion and 60 pounds force is too large to fit on the triceps cuff and is bulkier than the conventional cable control system. Again, there is not a problem with the slave cylinder because the excursion and force can be changed as long as the same mechanical work is transmitted to the prehensor. For example, it is possible to design the slave cylinder or actuator to produce ½ in. excursion and 240 pounds force, giving the same 120 inch-pounds of mechanical energy to the prehensor, thereby fitting in a smaller space. (In this case, the actuation point on the prehensor would have to be adjusted accordingly.)

DISCUSSION

After the proof-of-concept system showed promise, many ideas were generated and assessed before arriving at the additional two systems to build and test. One prototype each of the two additional systems was built. They were not clinically tested with amputees because they did not meet the requirement that the master actuator fit in a small space on the triceps cuff.

As part of the process of re-evaluating the three designs and identifying alternative technology, the author consulted with a number of people, including an industrial company specializing in hydraulics, staff at NASA Johnson Space Center, a space and aeronautics engineer who is a hydraulics expert, and a mechanical engineer with experience applying hydraulics to prosthetics.

All consultants agree that the approaches taken in the prototypes were reasonable, and that the key issue is the design of the master actuator to meet the functional and space requirements.

The idea of using pneumatics (gas) instead of hydraulics (liquid) has been suggested. For this application, pneumatics would be less satisfactory because gas is compressible and would (a) require more volume for the same mechanical energy delivered, (b) provide a "spring" coupling between master and slave, (c) have a lag in its response to rapid actuation, and (d) make socially unacceptable noise when vented to the outside.

CONCLUSIONS

The ultimate goal of this work is to improve body-powered, upper-limb prostheses by replacing the external cable and hardware of current designs with an internal hydraulic system, thereby allowing equivalent function with improved comfort, cosmesis, and acceptance. To date, the project has been unsuccessful in developing a suitable hydraulic replacement for the cable system. The key difficulty is the identification or design of a master actuator that can accept the necessary body excursion and force while occupying a small enough space to fit unobtrusively on the triceps cuff worn on the upper arm of the amputee. The author encourages further pursuit of the concept and recommends that future work be focused on the development of an acceptable hydraulic master actuator for the force transmission system.

Acknowledgments: This work is being supported in part by (a) Field-Initiated Grant No. 133MH70021 from the National Institute on Disability and Rehabilitation Research, U.S. Dept. of Education, (b) the Morris Stulsaft Foundation of San Francisco, and (c) NASA Ames Research Center, Technology Utilization Office.

REFERENCES

1. LeBlanc A. Innovation and improvement of body-powered arm prostheses: a first step. *Clinical Prosthetics and Orthotics.* 1985;9:13–6.
2. Trost J. A comparison of conventional and myoelectric below-elbow prosthetic use. *Inter-Clinic Information Bulletin* 1983;18:9–16.
3. Agnew PJ. Functional effectiveness of a myo-electric prosthesis compared with a functional split-hook prosthesis: a single subject experiment. *Prosthet Orthot Int* 1981;5:92–6.
4. Stein RB, Walley M. Functional comparison of upper extremity amputees using myo-electric and conventional prostheses. *Arch Phys Med* 1983;64:243–8.
5. Epps CH. Prosthetic-orthotic research—a new thrust is needed: a clinician's perspective. *Clinical Prosthetics and Orthotics* 1984;8.
6. Cottenden AM, Stocking B, Jones NB, Morrison SL, Rothwell R. Biomedical engineering—priorities for research in external aids. *Biomed Eng* 1981;3.
7. LeBlanc MA. Upper-limb prosthetics—current status and future needs. *Orthotics and Prosthetics* 1977;31:6–9.
8. Veterans Administration, Rehabilitation Research and Development Service. *National Workshop on Prosthetics and Orthotics, April 10-12, 1989.* San Francisco, CA.
9. Burgess EM. The road ahead: priorities for research. *Journal of Rehabilitation Research and Development* 1984;21(2):10–3.
10. LeBlanc, MA. Patient population and other estimates of prosthetics and orthotics in the USA. *Orthotics and Prosthetics* 1973;27:38–44.
11. National Center for Health Statistics, U.S. Department of Health and Human Services. *Prevalence of selected impairments—United States—1977.* Hyattsville, MD: US Department of Health and Human Services, Series 10, No. 134, Feb. 1981.
12. LeBlanc MA. Evaluation of cable vs. hydraulic transmission of forces for body-powered arm prostheses. In: *Proceedings of the 8th Annual RESNA Conference.* Washington, DC: RESNA, 1985:71–3.
13. Alderson SW. The electric arm. In: Klopsteh PE, Wilson PD, et al., eds. *Human limbs and their substitutes.* New York: Hafner Publishing Co., 1968.
14. Heather AJ, Smith TA. Helping hand, a hydraulically operated mechanical hand. *Orthopedic and Prosthetic Appliance Journal* 1960;14.
15. Smith TA. Hydraulics for power transmission in prosthetic devices. In: *The application of external power in prosthetics and orthotics.* Washington, DC: National Academy of Sciences, National Research Council, Publication 874, 1961:36–40.
16. Lewis DW. Hydraulics for prosthetic devices. *Orthotics and Prosthetics* 1968;22:23–8.
17. Goller H, Lewis DW. Hydraulic body-powered system for prosthetic devices. *Bulletin of Prosthetics Research* 1969;10–12:156–66.

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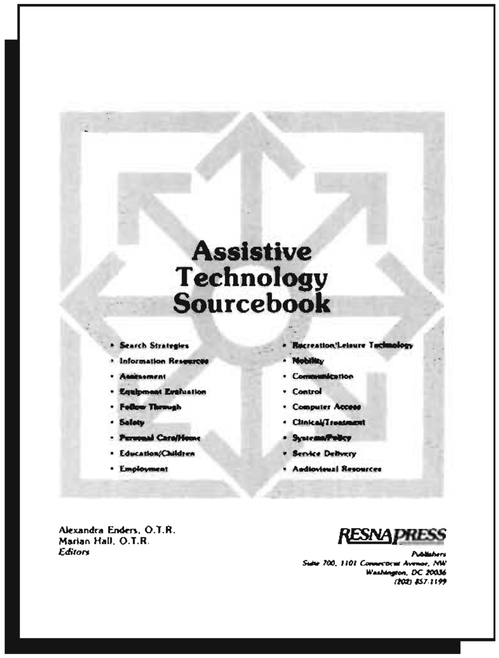

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