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A CASE STUDY OF TECHNOLOGY TRANSFER:

REHABILITATIVE ENGINEERING AT RANCHO LOS AMIGOS HOSPITAL

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REHABILITATIVE ENGINEERING AT RANCHO LOS AMIGOS HOSPITAL

Two generic problems encountered in attempts to rehabilitate disabled persons provide a useful focus for this case study of the transfer of aerospace technology into the area of rehabilitative medicine.

The first of these problems concerns the unique requirements of restoring a degree of motor function. The restoration process is unique because no two disabling conditions are ever identical. Designing a prosthetic appliance for an amputee can be based on previous general experience with and knowledge of commonly used devices, but each patient must be fitted individually. Application of external power and controls to an orthotic device for a paralyzed patient is often even more difficult, since residual motor functions vary with each patient. These residual capabilities provide the basis for building into an orthotic device the ability to voluntarily control the device. For example, one severely paralyzed patient might have the ability to flex an arm muscle slightly, while another can move a finger. In order to design systems that enable each to achieve voluntary control of his power and control apparatus, one system would have to be designed to harness inputs from the active arm muscle and the other from the movable finger.

Thus, the uniqueness of each patient's disability makes it quite difficult to build standardized control systems. Externally powered orthotic aids typically are fabricated on an individual basis at high cost. This level of expense often makes the technology inaccessible to many of the estimated 2.5 million disabled Americans who could regain some measure of mobility or function with the aid of orthoses (Badger, 1967).

The second problem concerns gaps in knowledge that affect the design and production of control systems and artificial limbs. Weight, power system capabilities, simplicity of construction and function, and similar design constraints make it difficult to define and build the "best" system for even a single patient. In addition, limited understanding of the physical forces and trajectories involved in limb movements is a factor that retards attempts to reproduce or augment these movements with finely engineered hardware.

Research and development (R&D) activities at Rancho Los Amigos Hospital in Downey, California, especially during the past twelve years, have contributed significantly to advances in engineering capabilities and growth in knowledge that has opened new avenues for standardizing engineering practice and reducing costs in the fabrication of control systems and orthotic or prosthetic units. Given the parallel interests of the hospital and NASA in areas such as miniaturization, safety, and efficient function of hardware, it should be no surprise that NASA-originated technologies have proved useful in the field of rehabilitative medicine.

This case study describes some transfers of NASA technology to rehabilitative applications at Rancho, in the context of the historical background of artificial limbs, the general technological problems of artificial limbs, some contributions of the new discipline of bioengineering to the general field of medicine, and the specific research and engineering environment of Rancho.

Historical Development of Prosthetic and Orthotic Devices

Coping with amputation or paralysis has been a problem throughout the existence of the human species. According to A. B. Wilson, Jr., crutches were devised from tree branches as an early tool-making effort. A 45,000-year old skull discovered in 1958 appears to have belonged to an arm amputee because the teeth had apparently been used to compensate for a missing arm. Herodotus wrote in 484 BC of a captured soldier who escaped from the stocks by amputating part of his foot and later replacing it with the first recorded wooden prosthesis. A copper-and-wood leg built about 300 BC was found in a tomb in Italy in 1858, and many iron prostheses made during the fifteenth century are presently in museums. Surgical techniques were improved markedly in the sixteenth century, and jointed artificial legs were invented to assist the increasing number of surviving amputees. Wooden legs were introduced in 1800, and numerous artificial limb patents were issued after the Civil War. Most of the advances in the general field, however, were in surgery, resulting in more functional stumps for fitting artificial limbs (Wilson, 1970).

Many ingenious efforts to make functional upper and lower extremity prostheses had resulted in an abundance of artificial legs, feet, arms, and crude articulated hands by the 1920's (Martin, 1925); but even up to 1945, the wearers of prostheses were overwhelmingly lower-extremity amputees. One reason for this is that most amputees are affected in the lower extremities (Wilson, Artificial Limbs, 1968). The more important reason was that prostheses were so primitive and nonfunctional that only the most severely impaired patients found their use worthwhile. A prosthetic leg, however crude, might enable a person to walk, but a good arm could eventually become an adequate substitute for two good arms, as compared with the alternative of having one good arm and wasting energy to cope with a poor artificial arm (Contini, 1967).

The Artificial Limb Program of the National Academy of Sciences was initiated in 1945 to promote more systematic improvement in prosthetic appliances, primarily to aid returning disabled veterans. The program was undertaken at the request of the Surgeon General of the Army. Simple mechanical improvements did not advance the state-of-the-art noticeably and immediately, and it became obvious that a basis of more fundamental knowledge of biomechanics was necessary for real progress. A new program emphasis was instrumental in funding and coordinating research that provided the fundamental data for improved practices during the past 15 years. Some 30 laboratories are involved in ongoing research supported by the Veterans Administration, the Department of Health, Education and Welfare, the National Institutes of Health, the Children's Bureau, and the Department of Defense (Wilson, 1970).

Nature of the Technology

The complexity of prosthetics and orthotics technology can be appreciated by considering the variety of medical problems for which replacement or support mechanisms may be necessary and by examining an engineering systems viewpoint of the problems.

In the most general sense, a prosthetic is any device that replaces a bodily structure and performs the function of that structure. Thus, dentures would be included in a complete list of prosthetic devices. Orthotic aids support and enhance the functions of intact but not fully functional body parts. Heart pacemakers and eyeglasses are examples. However, the common usage of the terms "prosthesis" and "orthosis" limits their application to devices that aid persons in the use of or substitute for their hands, arms and legs.

The kinds of disabilities most generally associated with orthoses include various levels of paralysis (hemiplegia, paraplegia, quadriplegia, or paralysis of single limbs) resulting from spinal cord damage or stroke, or diseases such as polio, cerebral palsy and multiple sclerosis. Arthritis and rheumatism sometimes cause structural and functional deterioration of bone joints and tendons that also may call for orthotic correction.

Prostheses are prescribed for upper limb amputations at the shoulder, above the elbow, at the elbow, below the elbow, at the wrist, across the hand, or at the fingers. Similarly, the lower extremities may be amputated at the hip, above the knee, at the knee, below the knee, at the ankle, across the foot, or at the toes. One or both sides and either or both extremities may be involved.

From a medical perspective, each of these disabilities calls for a different surgical and therapeutic approach and for a special kind of prosthetic or orthotic appliance. The multiplicity of variables carries over to an engineering perspective, where additional complications occur.

An engineering systems analysis of such problems begins by identifying the available control sites that can provide input signals for voluntary control of a prosthetic or orthotic device. There may be substantial muscle strength to initiate and power the device, as is common in the use of prosthetics. Where paralysis is the problem, the signal source may be electrical signals from muscles, the voice, eyeball movement, or some slight residual muscle function. The physiological signals must be converted to a useable input signal by means of some kind of transducer, be it a switch, valve, electrode, or a harness that transmits muscle force. Various kinds of signal processors must be considered if external power is to be applied; the control signal usually must be amplified and smoothed. The output system is the hardware driven by the processed signal, perhaps a wheelchair, an artificial hand or hook, or a powered splint. For any functional system there must be some means of feedback to the central nervous system, from vision, hearing, touch, or specialized muscle sensors. Local feedback is highly desirable for optimum operation of a powered system in order to prevent damage from excessive power application. Pressure sensors, slippage sensors, and position, velocity, or force indicators may provide this feedback (Reswick and Vodovnik, 1967).

Taken from a medical and an engineering standpoint, a multiplicity of solutions can be identified for any disability problem. But the problem-solving process is, in some cases, more complex. Although a technical solution may be agreed upon by a physician and an engineer, it may be impossible to apply the solution if the patient cannot or will not adapt himself to it. Because of these and other factors, large-scale advances in rehabilitation before World War II were considerably hampered. Only with initiation in 1945 of concerted and cooperative R&D programs involving physicians, engineers, and prosthetic and orthotic specialists has genuine progress been achieved.

Engineering in Medicine

To focus on NASA contributions of advanced technology to this field, it is necessary to deal preponderantly with engineering advances. A sampling of contributions to medicine in general from the new discipline of bioengineering helps convey a sense of the context within which NASA-originated technologies are transferred to specific patient applications at Rancho.

X-ray photography has been improved so that better results are obtained with less potential radiation harm to the patient. Infrared photography has been adapted for use in diagnosing conditions, such as rheumatism, that involve variations in blood supply to certain body parts. Ultrasonic techniques are now used in analyzing eye problems, locating breast tumors and destroying kidney stones. Fiber optic endoscopes are used to examine inaccessible interior areas such as the stomach. Electronic and optical technologies are used to record physical and physiological data with considerable precision, permitting better clinical observations and analyses. Computers are widely used as diagnostic aids. Heart-lung and kidney dialysis machines are indispensable life support mechanisms in many critical situations. Cryosurgery and lasers function as surgical knives in brain surgery and eye surgery.

Such successes of bioengineering are part of the intellectual environment at Rancho, where the process of adapting engineering knowledge to rehabilitative tools draws on all available sources. Aerospace technology is probably more important at Rancho than at other hospitals, since some of the most promising developments at Rancho have been achieved because of the availability of aerospace technology.

Rancho Los Amigos Hospital's Mission and Capabilities

Rancho Los Amigos Hospital is one of Los Angeles County's publicly supported health care facilities. It is the primary center for treating and rehabilitating patients with chronic diseases and physical disabilities. As a teaching hospital for the University of Southern California, Rancho also has access to advanced medical expertise. Many hospital staff members, engineers, and physicians hold academic positions at the university, and graduate students from the university learn and do research at the hospital.

Although the history of the institution extends back to the nineteenth century, rehabilitation became a dominant concern only after the Second World War. The polio epidemics of the 1950's placed great demands on the hospital, and, by the latter part of that decade, a clear interest emerged in developing research and engineering capabilities to enhance rehabilitation expertise.

Rancho pioneered in hiring engineers as professional staff members. At present, twenty research engineers are on the staff, representing specialists in electrical, mechanical, structural, chemical, and biomedical (systems) engineering. In addition, many of the staff engineers and electronics technicians have previous aerospace employment experience which serves to enhance the flow of aerospace expertise into the hospital's work.

Interaction with the aerospace industry began during the postwar period. In the late 1940's Northrop Aircraft Company assisted the hospital in applying aerospace techniques to improve prosthetic devices; and North American Aviation contributed to the design and fabrication of a sophisticated hydraulic-powered manipulator in 1954.

The demonstrated capabilities of the hospital staff, coupled with NASA interest in expediting the flow of aerospace technology into nonspace uses, has led to the award of NASA contracts to at least six staff members in recent years. The work performed in execution of these contracts highlights the nature of Rancho's contributions to technological advance in rehabilitative medicine; it also illustrates the various ways in which NASA and other aerospace technologies find useful applications outside their originally intended use in the space program.

R&D at Rancho

The range of investigations undertaken at Rancho has been quite large. A recent report of the work done on a ten-year project funded from several sources illustrates the breadth and depth of R&D undertaken by just one division of the hospital. A capsule summary from that report is presented as Table 1.

TABLE 1. RECAPITULATION OF WORK DONE DURING RANCHO'S CONTROL SYSTEMS PROJECT*

ITEM INVESTIGATED	HARDWARE PRODUCED	LABORATORY TESTED	PATIENT TESTED IN CONTROLLED ENVIRONMENT	CLINICAL TESTING	STANDARD PATIENT FITTING
Selector Device #1	x	x	x		
Selector Device #2	x	x	x		
Lever Valves	x	x	x	x	x
Pneumatic Connective Components	x	x	x	x	x
Flow Control and Quick Disconnects	x	x	x	x	x
Pneumatic Crossover System	x	x	x	x	
General Purpose Solenoid Valve	x	x	x	x	x
Sensitive Solenoid Valve	x	x	x	x	x
Sensitive Microswitch Control	x	x	x	x	x
Touchplate Control	x	x	x	x	
Light Beam Control	x	x	x	x	
Muscle Bulge Transducers	x	x			
Differential Transformer Transducer	x	x	x		
Proportional Pneumatic Valve	x	x	x		
Strain Gage Control	x	x	x	x	x
Null Balance Servo Control	x	x	x	x	
Multi-Axis Transducer	x	x	x		
Lever Switch	x	x	x	x	x
Pull Switch	x	x	x	x	x
Electric Handsplint	x	x	x	x	x
Battery Chargers	x	x	x	x	x
Tongue Switch	x	x	x	x	x
Motorized Tongue Switch	x	x	x	x	x
Bilateral Foot Control	x	x	x	x	x
Eye Control	x	x	x	x	
Button Control	x	x	x	x	
Proportional Wheelchair Control	x	x	x		
Power Steering for the Mono Drive	x	x	x	x	x
Pneumatic Wheelchair Recliner	x	x	x	x	x
Recliner Roller Lift	x	x			
Electro-Jack Wheelchair Recliner	x	x	x	x	x
Hydraulic Wheelchair Recliner	x	x	x	x	x
Mini-Pack Electric Wheelchair Recliner	x	x	x	x	x
Proportional Control Amplifier	x	x	x	x	x
Proportional Servo Amplifiers	x	x	x		
Telephone Dialer #1	x	x	x	x	x
Telephone Dialer #2	x	x	x	x	x
Telephone Dialer #3	x	x	x	x	x
Telephone Dialer #4	x	x	x	x	x
Tape Recorder Controls	x	x	x	x	x
Remote Controls for Dental Drill	x	x	x	x	x
Communications Device	x	x	x	x	
Hand Exerciser	x	x	x	x	
Electric Elbow Exerciser	x	x	x	x	x
Knee Exerciser	x	x	x	x	
Arm Exerciser	x	x	x		
Programmed Motion Control	x	x	x		
Friction Clutch	x	x	x	x	x
Implant Transducer	x	x	x	x	
Handwriting Manipulator #1	x	x			
Handwriting Manipulator #2	x	x			
Joystick Control for Handwriter	x	x			

* Source: Allen, J. R. and A. Karchak, Jr., 1970.

Perhaps more important than the variety of investigations completed during the lengthy project is that most of the investigations proceeded to the point of achieving standard patient fittings of the hardware items. It has been a firm policy at the hospital to carry development work to the point of at least designing a production model of a useful device and to encourage manufacturers to produce the items. This point is more fully discussed in a later section.

NASA-Funded R&D at Rancho

With this perspective it is easier to comprehend the importance and potential impact of R&D conducted at Rancho in cooperation with and, in many cases, with funding from NASA. Several NASA-funded activities are discussed in the following section, ranging from orthotic manipulators to tiny DC motors. The perspective is that of engineering systems analysis, which deals with complete systems such as orthotic manipulators and with each subsystem in relation to the whole, such as transducers which detect and transmit voluntary control signals, proportional velocity controls which process the signals, and terminal devices which translate the signals into useful output for work.

Orthotic manipulator arms. A man in space is relatively helpless in many respects; to perform useful work, he has to have special tools and some kind of assisting control mechanisms. The Atomic Energy Commission (AEC) has long been interested in perfecting remote manipulators for safely handling radioactive materials from a distance by human operators. These interests coincided with some of NASA's interests, and both groups recognized the significance of advances in externally powered arm braces that had occurred at Rancho. The combined efforts of all three organizations have advanced the sophistication of remote manipulators and of externally powered orthotic manipulators.

Orthotic manipulators resemble the human arm in construction and operation. In medical applications they restore arm function to paralyzed patients, while industrial, scientific, and space uses emphasize "teleoperator" characteristics in a master/slave mode that duplicate human motions at a distance.

NASA and AEC sought Rancho Los Amigos Hospital assistance in improving teleoperators largely because of the hospital staff's success in developing a powered orthosis, the Rancho Electric Arm (REA). Beginning in 1959 with pneumatic (compressed air) power sources, Rancho investigators determined that a functionally useful arm must have at least seven joints, or degrees of freedom, and they specified optimum alignments, locations, power requirements, angular velocities, and functional ranges of motion. In addition, they ascertained the characteristics and potential of control sites in various types of patients. Intensive analyses of normal arm motions enabled the team to specify operational mechanical configurations to approach as nearly as possible a duplication of normal arm function (see Figure 1).

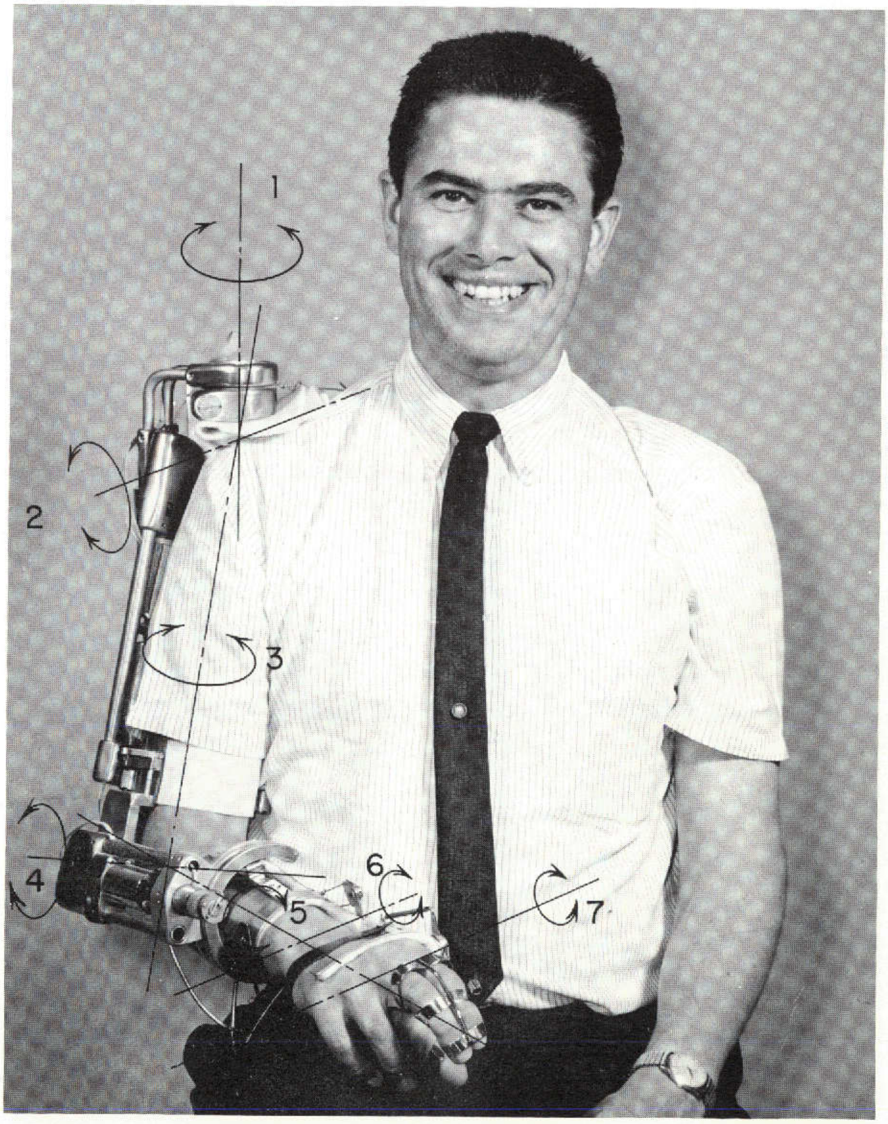

Figure 1. A Rancho Engineer Models the REA; the Seven Degrees of Freedom are Indicated with Arrows.

After four years of work with pneumatic power, it was decided that an earlier consensus in the profession--that electrical power was inferior to pneumatic power (National Research Council, 1961)--was no longer valid enough to preclude new explorations in electric power and control systems. The advantages of pneumatic systems were recognized: weight and cost of actuators were less than for electrical actuators; less noise is generated in the pneumatic system; and complex pneumatically powered orthoses were as much as 30 percent less costly than comparable electrically powered units. However, the advantages of electrical systems were more numerous and compelling. Among these are the greater ease and cheapness of replenishing the power source; greater efficiency of energy storage (by a factor of 10); no need to convert electronic control signals for pneumatic actuators; greater simplicity, versatility, and inexpensiveness of control signal processing units; availability of mass produced, low cost electronic components (versus individually produced costly pneumatic components); availability of a rotary output from an electrical actuator, which meets the need for rotary motion of the dynamic joints of an arm brace without a mechanical conversion of linear to rotary motion; and, very significantly, the ability to use a single energy system to provide ample power for both a wheelchair and an orthosis.

Development of the REA thus proceeded from the broad foundation of successful experience with pneumatically powered orthoses. By early 1965 an operational electric arm had been fitted to a patient for complete testing, evaluation and necessary modifications. Using the current version of the arm, this patient, who became a quadriplegic polio victim in 1954, is now able to perform many ordinary tasks of daily living, including writing, typing at 25 words per minute, and operating a modest telephone answering business.

Under contract to Marshall Space Flight Center, Rancho's orthotic arm expertise has been directed toward development and fabrication of four remote manipulators. A bilateral remote manipulator delivered to Marshall was based on earlier arm designs and incorporated several improvements. Among these were two redesigned joints in the master controller brace and lighter, stronger, and more efficient slave arms (see Figure 2).

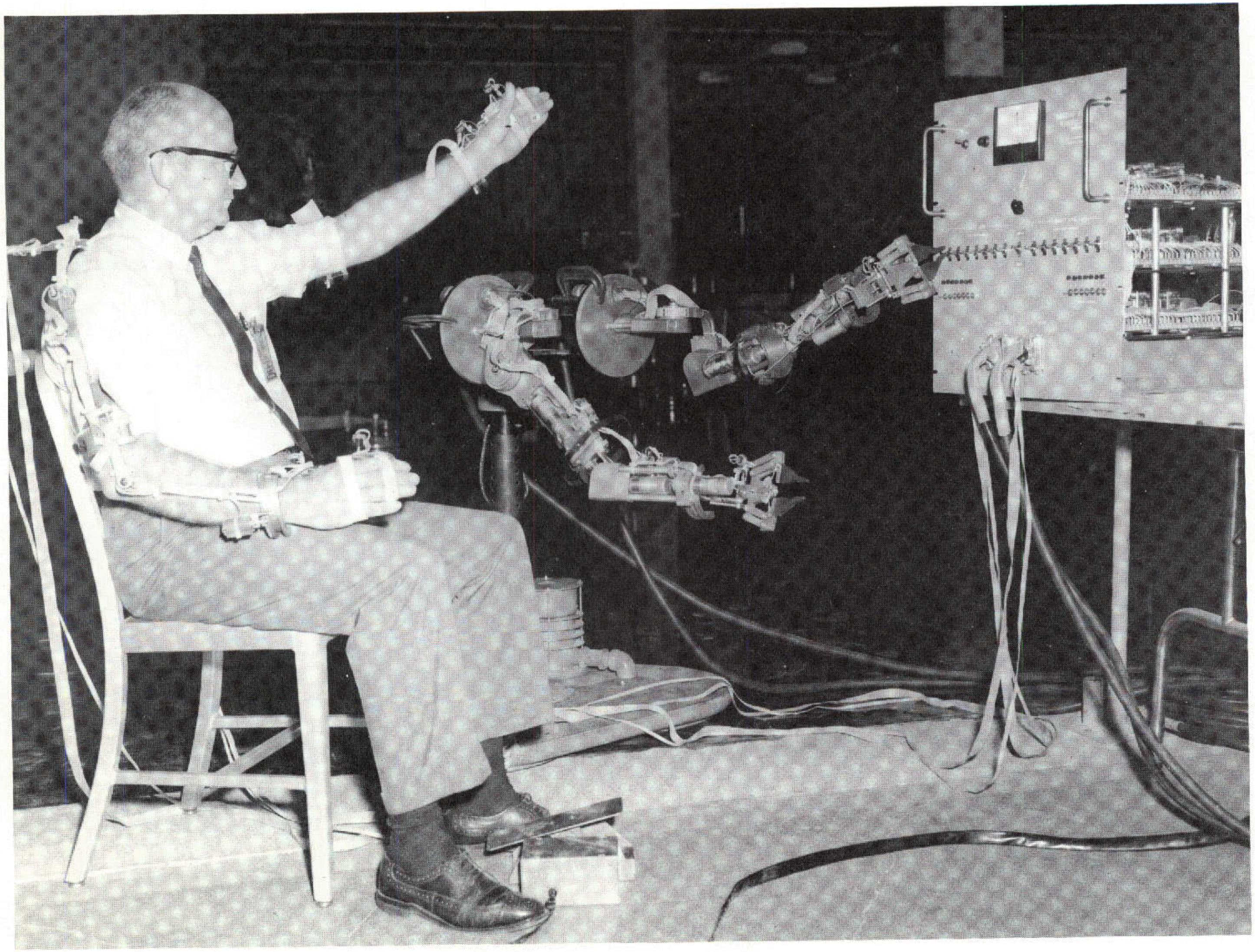

Figure 2. The Bilateral Remote Manipulator.

A self-propelled anthropomorphic manipulator (SAM) was built for use at the Atomic Energy Commission's Jackass Flats nuclear engine facility. SAM is mounted on a motorized vehicle that is remotely controlled by telemetry as it travels about an area of hazardous radioactivity. The manipulator arms are also remotely controlled to do useful work in the hazardous environment. Rancho helped build a controller for an extendable stiff arm manipulator (ESAM) for NASA's use in simulating and investigating problems of cargo handling and other work activities in space. This unit has a capability for locking and unlocking the analog arm joints on command from the operator. Finally, the Rancho Anthropomorphic Manipulator (RAM) exists as a demonstration prototype. RAM has the capability of operator-controlled terminal device replacement. It is mounted on a "shoulder" that allows side-to-side and forward-backward movement of four inches in each direction, as well as arm movement within the radius of the arms. Its size and power are much greater than those of the Rancho Electric Arm; RAM can lift and transport a ten-pound weight. Several control systems can be used, including a joystick. Development emphasis has been on a master/slave system with an exoskeleton control apparatus for the operator.

Beyond the immediately useful improvement of teleoperators that enable men to perform work in hostile environments, these research and development activities have enhanced Rancho's expertise in its area of major concern: rehabilitation of the disabled.

Transducers. All functional artificial limbs require transducers to generate a control signal that culminates in a desired limb motion. Conventional prostheses utilize harness mechanisms and mechanical linkages to generate the control signals. Pneumatically powered systems, by contrast, convert muscle force to control signals for the gas-powered actuators. Electrically powered systems can utilize many input transducers that generate or pass an electrical signal. The most obvious would be the fairly common microswitch. More exotic is the piezoelectric crystal that emits electricity when compressed. It is safe to say that nearly every kind of transducer that might be useful for controlling artificial limbs has been evaluated at Rancho, and many types have been at least experimentally incorporated into the research programs of the hospital.

A transducer that provides inputs from any axis in a single plane would greatly simplify orthotic control systems operation. The joystick control originally developed for high performance aircraft weapons control systems achieves such a result; the stick can be moved throughout a full circle and different portions of the circle designated for specific outputs. Its main advantage in an orthotic device is that several motions of the arm can be controlled by a single input transducer.

Rancho personnel have built functional analog joysticks for use with ESAM. The ESAM joystick was designed specifically for the manipulator; however, a more generally applicable version was also built and can be used with any type of teleoperator. Potential applications beyond aerospace and orthotics uses include mining, undersea work, or any activity involving hazardous environments. For orthotic devices, the analog controller can be used handily by patients who have only minor paralysis.

Perhaps the most intriguing and promising transducer work at Rancho is directed toward perfecting tongue-operated controls. Experience with paralyzed patients has shown that the tongue is an extremely versatile muscle. The Rancho Tongue Switch presently used by many patients provides completely convincing evidence of the utility of the tongue for controlling complex systems. Even though the model now available is mounted on a wheelchair and is operated from a position in front of the operator, which requires constant extension of the tongue outside the mouth, it has been readily accepted by patients.

Studies at Rancho indicate that the tongue is even more versatile when allowed to perform inside the mouth. Thus, an intra-oral control unit would be superior to the external type; in addition, an intra-oral unit would not obscure the operator's vision and diminish the quality of visual feedback. Initial development of an intra-oral system is underway at Rancho. It must have multichannel capability, since the electric arm requires a minimum of 14 channels to achieve bi-directional control of each of the 7 joints. In order to fit inside the mouth, small size is essential; this limits the choices among possible transducers. Also necessary are ultra-thin printed circuit materials. Flexible mounting substrates for the printed circuits would simplify construction processes for the control unit. Some of these specifications were met in a NASA-funded invention by Dr. Richard Muller of the University of California at Berkeley. Dr. Muller's insulated-gate field-effect transistor (IGFET) is a hybrid thin film and piezoelectric transducer that incorporates sensors and an amplifier in the same package. For the intra-oral control unit, 14 IGFET's will be mounted on a flexible printed circuit substrate which will be attached to a dental bridge. Tongue pressure on a nylon ball atop each IGFET will generate a signal proportional to the applied force, not merely an on-off signal (see Figure 3). An antenna mounted on the bridge will transmit the control signals to the actuators.

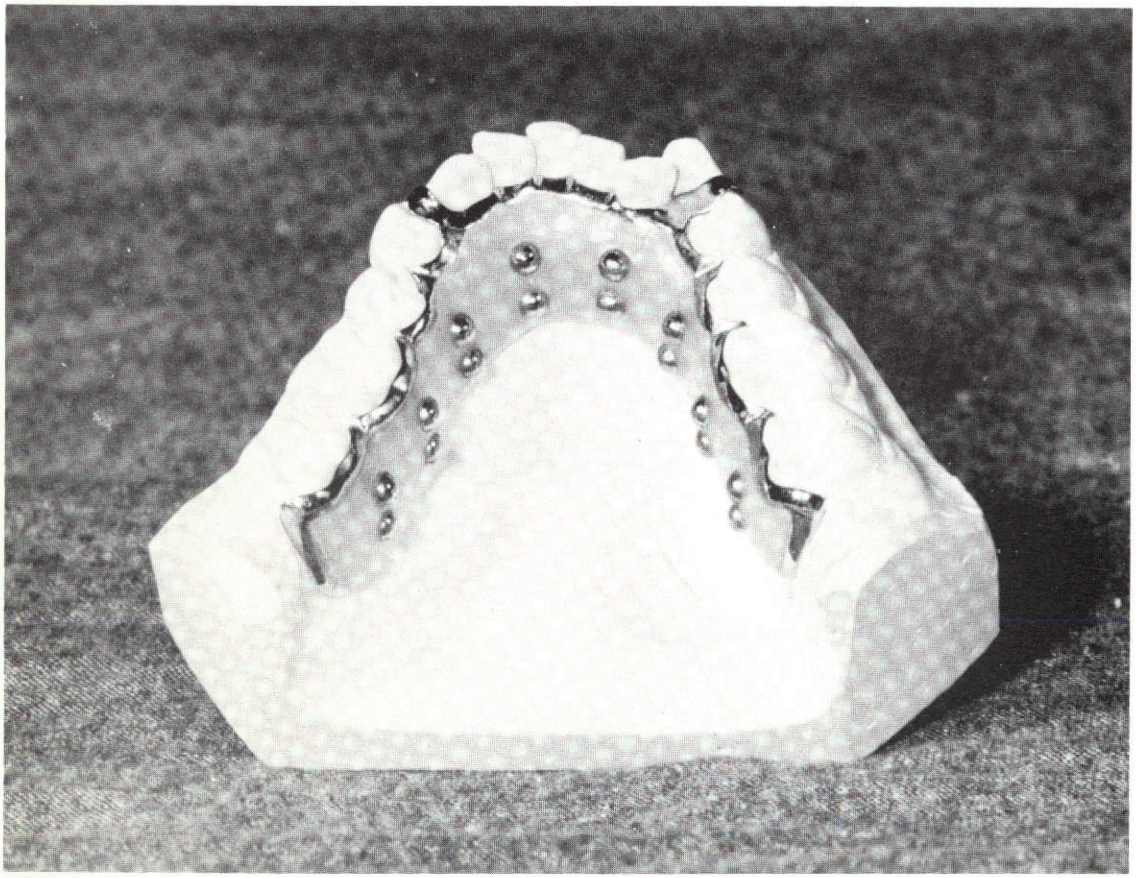

Figure 3. A Model of the Intra-Oral Control Unit.

Proportional velocity controls. In the standard teleoperator or powered artificial limb, the control signal is an on-off type: energy is either delivered at the full capacity of the specific channel or is not delivered at all. This characteristic makes it extremely difficult to perform small, refined motions, especially when the arm has come to rest near the location at which the small motions are desired. The inertia of the actuator and motor presents an obstacle to making a slight displacement of the arm, and an on-off control switch places a full voltage load on the motor instantaneously. This tends to drive the arm past the desired position. A more desirable type of control is a proportional velocity control which delivers energy in a full range of magnitudes, from very slight input to achieve slow motion for fine movements to a large input to move a limb segment rapidly from one position to another.

Under a NASA contract, Rancho designed and built a miniaturized unit (7" x 5" x 4") for teleoperators, which achieves proportional control signals through pulse rate modulation. The initial signal to an actuator is characterized by a slow pulse rate which begins a slow output motion. A prototype built in 1970 was subsequently upgraded by incorporating solid state components. Further size reduction was achieved before delivering the final product to Marshall Space Flight Center. Tests of the unit have demonstrated its ability to deliver smooth and chatter-free control movements without noticeable time delay between the master and slave systems. Orthotic applications are now being evaluated in clinical settings at Rancho, Walter Reed Army Hospital for the Veterans Administration, the Texas Institute of Rehabilitation in Houston, and the Moss Rehabilitation Center in Philadelphia. The National Research Council's Committee for Prosthetic Research and Development is coordinating the evaluations.

Terminal devices. An orthotic manipulator's ultimate effectiveness is quite dependent on the capabilities of the terminal device with which the desired work is accomplished. Artificial hands are impressive for their cosmetic qualities, but most upper extremity amputees prefer simple hooks which are, despite their appearance, considerably more functional than the best commercially available artificial hand.

Two NASA-supported projects at Rancho are concerned with improving terminal devices. A project conducted by General Electric in cooperation with Marshall Space Flight Center personnel resulted in an electromechanical jaw with touch sensors to ensure a safe and uniform grasp, concealed fingers that actuate for triggering a hand tool, and a structural geometry that permits work on a flat surface. Rancho staff members have adapted some of the features of this teleoperator system to a prosthetic hook with which an amputee can operate power tools. A unique shoulder-harness multi-position switch and a kind of "automatic transmission" in the hook actuating mechanism enable the user to grasp a power tool firmly, engage the tool trigger, release the trigger, and then set the tool aside in four distinct motions. The prosthesis is undergoing laboratory evaluation, with successful fitting on and operation by two patients. Figure 4 shows one of the patients using a power drill.

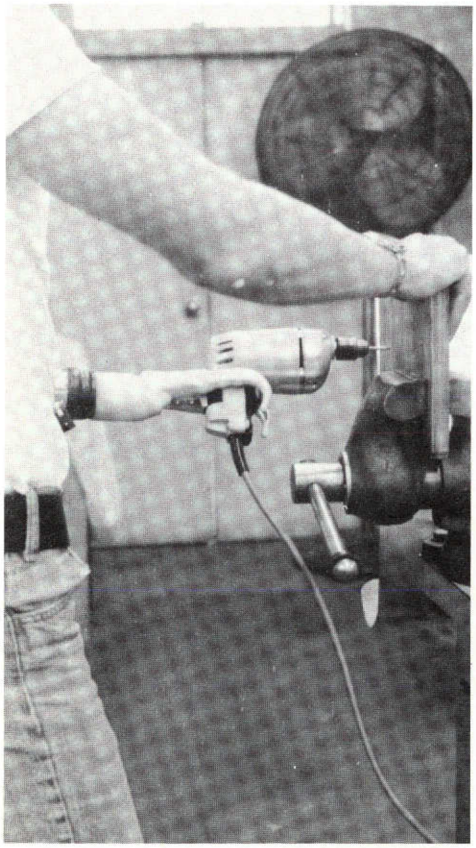

Figure 4. A Rancho Patient Demonstrating the Powered Hook.

While this advance is significant, many other actions cannot be accomplished with prosthetic hooks or with the ordinary jaws used with teleoperators. A current contract between Rancho and NASA's Marshall Space Flight Center is directed toward increasing the number and kind of tools that can be used with orthotic manipulators. The basic product of the project will be a "Terminal Kit Assembly" consisting of a number of hand tools (e.g., socket wrenches, pliers, cutters) and a terminal device to pick them up and use them. The hand tools are being redesigned to facilitate attachment by the terminal device, and a special tool storage bin is being designed to hold tools when they are not in use. New drive, linkage, and connecting mechanisms to improve teleoperator operation are under development. It is anticipated that this project will provide valuable experience for applying the concepts in better prosthetic hands.

Biocarbon implants. Advanced concepts in the artificial limb field aim at creating closed-loop systems technologies, in which the body's own internal feedback mechanisms can be coupled to external power and control systems. Many kinds of feedback occur naturally, but knowledge of their complex mechanisms is still inadequate to use the internal processes for controlling external systems. Even more limited is the technology that would be necessary to detect and utilize the body's feedback system. One of the very serious obstacles to any kind of implantable device that might be used in a closed-loop system is the incompatibility of most materials with the human body; either the body fluids degrade the materials, or a rejection phenomenon occurs, or both.

A breakthrough in the materials field was announced in a 1969 NASA Tech Brief authored by James Benson of Rockwell International Corporation. Benson's evaluations of several high-strength carbon composites that had been developed for aerospace uses indicated that these materials are chemically, physically, and biologically compatible with human body fluids and tissues. Benson anticipated medical uses of the materials as cosmetic and protective bone replacements, implantable splints, circulatory bypass implants, replacement heart valves, implantable prostheses, and implantable myoelectric probes to detect electrical activity in muscles.

Substantial evaluation of these possible uses for biocarbon has occurred and is continuing at Rancho with NASA funding. Among the investigations that have confirmed the biocompatibility of the materials are studies of variously configured transcutaneous implants. The devices are the only known materials that can be implanted to pass through the skin without inducing infection at the site. The skin heals around and attaches to the implant with no adverse effects. Several patients are wearing implants to which leads are attached in order to conduct electricity from a battery pack into the body for pain suppression, for myoelectric electrodes, and for skeletal attachment of limb prostheses or skeletal traction devices. Experiments are planned for additional skeletal attachment configurations, and myoelectric electrode possibilities will be explored in depth, both for sensing and stimulative purposes.

Brushless DC motors. An important design specification for orthoses and prostheses is that the devices must be light in weight. Therefore, the actuators must be small, but they must also deliver adequate energy to power the artificial limb. Finally, cosmetic considerations call for minimum noise.

In cooperation with the Jet Propulsion Laboratory, Rancho is preparing to test a brushless DC motor which was originally described in a 1966 Tech Brief from Goddard Space Flight Center. In space, a conventional DC motor will fail rapidly because the vacuum conditions cause the commutator brushes to "weld" to whatever surfaces they touch. Goddard engineers invented an optoelectric commutator to replace the brushes and eventually designed a motor having a wide range of speed and torque and excellent response time. In addition, there is no arcing; the unit can be completely sealed; and, distinctly advantageous for an artificial limb system, the motor's speed and torque can be controlled precisely by external electronic circuits. Rancho personnel expect that the motor's high electrical-to-mechanical conversion efficiency will permit use of very small units, providing good torque at low speeds. The latter capability allows an arm design with low speed gearing mechanisms which are less noisy than others.

Establishment of External Diffusion Mechanisms

The innovators at Rancho Los Amigos Hospital long ago recognized the futility of achieving significant improvements in their laboratories if only their immediate patients were to benefit. Longstanding hospital policies encourage the use of several channels through which in-house research and development results are communicated to professionals in many fields. The standard practice of publishing research findings in professional journals is followed by all staff members. During the last ten years, papers have been published by the staff in journals such as IEEE Spectrum, Mechanical Engineering, Annals of Biomedical Engineering, Artificial Limbs, Bulletin of Prosthetics Research, Journal of Prosthetics and Orthotics, Orthopedic and Prosthetic Appliance Journal, Journal of Bone and Joint Surgery, Southern Medical Bulletin, Archives of Physical Medicine and Rehabilitation, and others. Staff members regularly participate in conferences and symposia sponsored by the National Academy of Sciences' Committee on Prosthetics Research and Development (CPRD) and other national and international groups; in addition, several serve on advisory boards of the Social Rehabilitation Service in the Department of Health, Education and Welfare, the Veterans Administration, and the CPRD.

One of the most significant diffusion channels for Rancho advances exists because of a hospital policy that all useful hardware resulting from research should be developed to the point of commercial manufacture. The hospital actively solicits manufacturer interest in producing the devices, and some manufacturers have established continuing research collaboration arrangements with the hospital. Among the companies that have entered into manufacturing or research affiliations with the hospital are Medtronic, Incorporated, Bentley Laboratories, Orthopedic Supply Company, Electro Limb Corporation, B&L Engineering Company, R&D Engineering Company, Neilson Zane Electronics, McCullough Corporation, Cutter Laboratories and Mattell Toy Corporation. Of those devices discussed in this report, Rancho Electric Arms and proportional velocity controls are available as standard items from Hosmer-Dorrance Corporation, while industrial remote manipulator arms are available from Electro Limb Corporation. Tongue switch transducers are manufactured by B&L Engineering. Various terminal devices are made by Hosmer-Dorrance Corporation. Several firms, including Cutter Laboratories, Medtronic, Incorporated, Hosmer-Dorrance Corporation, and Syntex Corporation, are involved in supplying biocarbon devices. Through these and other firms, the goal of eventually making devices available on a nationwide basis is served. In this way, many advances of new technology in orthotics and prosthetics can come to benefit a much larger proportion of the disabled.

Conclusion

These examples of the successful transfer and diffusion of advanced aerospace technology into an area of rehabilitative medicine, where the engineering requirements are often quite similar to those of NASA, illustrate several of the formal and informal mechanisms by which such transfers occur more generally throughout the economy. The value of technology transfer in rehabilitative medicine can be appreciated chiefly by recognizing that aerospace advances have made it possible for engineers in medicine to design and build functional power and control systems for the disabled. While each patient has unique problems and needs, causing systems to be tailored on an individual basis, the possibility of large-scale rehabilitation assistance from powered artificial limbs is more of a reality because of adaptation of aerospace technology to the field. Standard components are now becoming available, and they can be used in many instances regardless of the unique conditions and needs of different patients.

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