NASA SP-363

TECHNOLOGY AND THE NEUROLOGICALLY HANDICAPPED

A conference held at
AMES RESEARCH CENTER
Moffett Field, California
September 8–10, 1971

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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A conference cosponsored by the
National Aeronautics and Space Administration and the
United Cerebral Palsy Foundation and held at
Ames Research Center, Moffett Field, California,
September 8–10, 1971

Prepared at Ames Research Center

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FOREWORD

The Conference on Technology and the Neurologically Handicapped was co-sponsored by the United Cerebral Palsy Foundation and the National Aeronautics and Space Administration. The Conference was held at the NASA Ames Research Center on September 8, 9, and 10, 1971. It was attended by a large number of specialists from various government agencies, voluntary health organizations, universities, and hospitals, and from companies with expertise in the advanced technology relevant to the needs of the neurologically handicapped.

The inspiration for the Conference came from Dr. Lee Arnold, Chairman of the Department of Aeronautics and Astronautics at New York University, and from his colleagues in the United Cerebral Palsy Research Foundation, particularly Dr. William Berenberg. The Conference was actively supported also by the Chairman of the United Cerebral Palsy Foundation, Mr. Leonard Goldenson. Illness prevented Mr. Goldenson from being present at the meeting, but his place was taken with charm and inspiration by his wife, Isabel Goldenson. Within NASA Dr. George Low, the Deputy Administrator, and Dr. Hans Mark, Director of the Ames Research Center, were responsible for instigating the meeting. At the Ames Research Center, Dr. Harold Klein, Director of Life Sciences, and Dr. David Winter, Deputy Director of Life Sciences enthusiastically made their resources available to implement the Conference.

It was my pleasure to assist Dr. Lee Arnold, Chairman of the Conference, with the organization and execution of the meeting. We must acknowledge the major contributions made to the meeting by the authors of the individual papers, and to the Chairmen of the Sessions, who held up valiantly in the face of the perennial conflict between the desire to let first class discussions continue late into the evening and the need to keep the meeting on schedule.

The Conference began with presentations of the major problems by the representatives of private and government organizations working with the neurologically handicapped, and with accounts of clinical approaches to current methods of treatment by medical and rehabilitation experts. The second day was devoted mostly to new approaches being actively pursued or under consideration. Here the orientation was more towards neurophysiology and engineering, and included a strong flavor of some of the recent technological advances in the areas of control systems, man-machine integration, and novel engineering concepts.

The third day was devoted to general discussions, led by specialists from the fields of clinical neurology, neurophysiology, engineering and rehabilitation.

In editing the proceedings of the conference we have tried to retain as much as possible of the impact of the spoken word and the give and take of the discussions which took place. However, papers that included demonstrations clearly do not have as great an impact in written form as they did at the conference itself.

Finally I would like to express my thanks to all who contributed so much to the success of the meeting and the preparation of this volume, in particular, Bruce Castle, who made a major contribution to the editorial work, to Mrs. Pat Brown and her colleagues for their assistance with the secretarial work and the organization of the conference; to the Ames Manuscripts Branch for their fine work in compilation and printing; and last but not least, I must single out my colleagues in the Life Sciences Directorate and the Instrumentation Division at Ames who arranged demonstrations of their own work for the participants at the meeting.

John Billingham

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Chapter 1

THE CONCEPT OF TECHNOLOGY TRANSFER

Lee Arnold
Chairman, Department of Aeronautics and Astronautics
New York University

This volume describes some of the potential benefits from aerospace and other technology-oriented disciplines that will enable the neurologically handicapped to recapture and upgrade some of their motor and sensor functions. By *neurologically handicapped* is meant all individuals whose motor-sensory communication systems have been damaged as a result of disease, trauma, or aging. There are on the order of a million patients afflicted with cerebral palsy. When you add to this the victims of stroke and other disabling afflictions, we have a tremendous number of neurologically handicapped individuals today. Means of enabling them to function to the greatest possible extent are urgently needed not only from the humanitarian standpoint, but for obvious economic reasons.

The possibility of technology transfer to aid the neurologically handicapped has received increasing attention in the past few years. To explore the potential role of NASA's technology utilization group in this area, a conference was arranged some years ago at NASA Headquarters, which brought together members of the technology utilization and biomedical staffs of NASA and a selected group of biomedical experts recommended by UCP. The meeting met with a great deal of enthusiasm, but it was somewhat limited in terms of the participating organizations, and of the problem areas addressed.

More recently, the question of applying technological developments to the problem of mobility of the neurologically handicapped was raised by UCP. As a result, members of UCP staff met with members of Grumman's Lunar Module staff to become acquainted with systems concepts and to explore design alternatives for mobility units. The encouraging and fruitful results of this meeting are discussed in Chapter 20.

The aerospace engineer involved in the stability of flight is dealing with what are referred to as *aeroelastic problems*. The physical scientists and engineer often makes use of analogies in treating his problems. In studying electric circuits, we often refer to *mechanical analogs* and the reverse. In a sense, the neurologically handicapped individual is somewhat analogous to the pilot of an inherently unstable airplane, a view that suggests the potential relationships between the aerospace work of NASA and of other technology-oriented organizations and the applications of interest to UCP. This possibility was explored still further in meetings with UCP, Ames staff, and DOT representatives, and ultimately led to the conference documented here. (It should be noted that the Department of Transportation is not only extremely concerned with problems of mobility and transportation of the handicapped, but is permitted by an amendment to the Urban Mass Transportation Act to allocate 1.5 percent of all money spent on urban transportation to problems of the handicapped.)

During these preliminary meetings, the potential applications of NASA's technology to the problems of the neurologically handicapped were discussed with a great deal of enthusiasm, and many intriguing questions were raised. For example: Is it possible to introduce filtering devices that would remove the erratic behavior from the neurologically damaged? Is it possible that NASA developments in tele-operator research, artificial intelligence, and so forth, could be applied for similar purposes? What are the possibilities of applying some of the work in vehicle design, based on postural control, for example, that going on at MIT and Grumman, to the design of transportation vehicles easily controlled by a disabled individual, to achieve mobility within the home, out of the home, and on the street, as well as in finding means of coupling into public transportation systems?

The conference reported here grew out of these initial discussions and is, I feel, a major step toward determining the state of the art and the extent to which existing technology is utilized by the medical profession. Hopefully, this undertaking will stimulate continuing efforts by technology-oriented organizations, NASA, and the Department of Defense, to work with the various user agencies – HEW, the Department of Transportation, the Veterans Administration, and some of the private foundations such as UCP – toward the effective transfer of technology for the benefit of the neurologically handicapped.

Chapter 2

NASA AND TECHNOLOGY

DeMarquis D. Wyatt
Assistant Administrator for Policy and University Affairs
NASA Headquarters

This conference centers on the problems of the neurologically handicapped and the potential contributions of science and technology to the development of means of enabling these people to cope with a normal environment. An important area of concern in NASA's aeronautical and space programs is that of understanding the stresses on and responses of normal individuals – aviators and astronauts – to an abnormal environment, and the development of devices to help them cope with that environment in a safe and effective manner. It is not surprising, therefore, that NASA research and development in the area of man's responses and accommodations to unfamiliar environmental stresses should bear a close relationship to the medical community's concerns with the neurologically handicapped, particularly at the level of technological assistance devices.

The same kind of technological correspondence occurs repeatedly between NASA's activities and other problem areas of concern that may seem at first blush to have no commonality. In part, these relevancies occur because mankind is dealing with a limited number of basic scientific and technical disciplines, and the advancements within one discipline tend to find a natural marketplace among other discipline practitioners. To a much larger degree, however, the relevance of NASA's activities to nonaerospace problems is a result of NASA's basic approach to the solution of its own technical problems. In other words, it is not so much what we do; it is how we do it.

NASA's assigned mission is to explore the unknowns of space, and to devise techniques and systems to translate the knowns into practical beneficial applications for the benefit of mankind. We have the same responsibilities in aeronautics, except that the proportion of scientific unknowns about the Earth's atmosphere is relatively small, and our principal task is the technological advancement of practical aeronautical systems.

How NASA's mission assignments are to be accomplished was not and cannot be specific in the enabling legislation. NASA has had to develop its own guiding principles and philosophies in this regard, and we have elected to pursue an in-depth understanding rather than a cut-and-try approach to our technological developments. *In-depth understanding* refers to an approach that goes far beyond the basic determination that a component or a subsystem performs within its design limits, to a level of understanding of why the device performs as it does and what its tolerance limits are in response to external variables. To accomplish this, it is necessary to understand the phenomena or functions embraced and affected by the subsystem in question.

Both in-depth and cut-and-try approaches can lead to entirely satisfactory end results, but there can be marked differences in the development cycles. Consider some contrasting experiences in the development of space booster vehicles, for example. The Atlas space booster, derived from the IBM missile launcher, ultimately became a reliable workhorse vehicle in our stable of space boosters. It was developed using an approach that was typical of the "cut-and-try technique." You may recall the period early in the space age in which we were reassured, and correctly, that the country was learning more from launch failures than from the occasional launch successes. In the manned space flight program, John Glenn became the first American astronaut to achieve orbit and his Project Mercury spacecraft was launched by the Atlas booster. The booster was serial no. 104, and the vehicle was still in the development stage. The Saturn V booster for the Apollo Program, on the other hand, was developed using NASA's in-depth approach. The first manned flight using this booster, in an orbit of the Moon by Borman, Lovell, and Anders, was launched by the third Saturn V vehicle. This relatively unprecedented rate of achievement of booster operational status illustrates one of the benefits of NASA's approach to technological developments.

Other facets of the interface between NASA's technology and the broader more diverse concerns of our society are of greater interest for our purposes here. That an in-depth approach to technology requires an understanding of both the functions and the environment of the proposed solution is not a novel thought. Our common experiences long have taught us that the identification of a problem is a major part of the solution. It is essential, however, that the true nature of the problem and the solution be understood, rather than the apparent nature, if we are to have confidence that the right problem is being solved, or that the correct solution is being considered.

We are frequently apt to reserve serious study only for very complex problems and to rely on our experience or intuition to identify or classify a simple problem. But NASA has found that it pays to ensure a thorough understanding even of the apparently simple problems. A few years ago, for example, NASA undertook some research in the category of aircraft operating problems to see what could be done to reduce the incidence of aircraft skidding on wet runways. Now, any high school physics student will tell you that the coefficient of friction between the tire and the runway decreases under wet conditions, and that the higher coefficient should be sought in changes of runway texture or tire tread designs. As research progressed, however, and a better understanding of the problem was developed, it became clear that this was not the sole or even the major cause of many skidding incidents. Instead, it was found that when moisture accumulated to form a discrete surface layer on the runway, the aircraft wheel would, under certain conditions, actually hydroplane on the water layer. Under this condition, the wheel rotation would come to a complete halt without the brakes being applied and directional stability would be completely lost. Under these circumstances, considerations of rolling or sliding friction coefficients were no longer applicable. It was found that the onset of hydroplaning could be quantitatively described solely in terms of aircraft speed and tire pressure; neither tread design nor runway texture had any first-order effect. Once this correct fundamental understanding of the nature of the problem was achieved, it was possible to devise practical solutions. Various runway grooving patterns were evaluated not to provide texture but to assist in water runoff and to reduce the effective depth of residual water. Furthermore, once the fundamentals of the problem were understood, applications of the study results to other, broader problem fields became obvious. In particular, the phenomena uncovered seemed to explain the particularly treacherous nature of certain stretches of high fatality highways. Since the significance of this research was brought to the attention of the state highway departments, grooving has been beneficially applied to sections of highways in several parts of the country.

The possibilities for technological transfer of NASA-developed concepts to other problem areas are enhanced by the more fundamental understandings brought out by the in-depth approach, but such transfer is by no means quick and automatic. The quick transfer is often confined to cases where direct *imitation* is possible, as illustrated by the application of grooving to highway surfaces cited above. When the technology transfer process is *adaptive,* the opportunities for imitative transfer are necessarily limited, and greater values are apt to be realized by the nonaerospace sector. In this case, the principles underlying a concept are grasped and applied in principle, rather than in kind, to appropriate situations and systems. Such adaptive transfers are necessarily slower and more difficult than the imitative transfers. The potential user must be aware of the existence of a technological concept and must comprehend the principle that is applicable to his problem area.

NASA recognized that the process of technology transfer warranted special attention, and became one of the first government agencies to set up a full-time program to enhance the systematic exchange of technology to other sectors of our society. A variety of techniques have been adopted to improve the transfer process, and even more effective mechanisms are still being sought. One of the latest approaches has been the formation of biomedical technology transfer teams in several areas of medicine. These teams bring together medical and aerospace engineering consultants to provide a forum for consideration of problems and potential solutions.

Yet another transfer mechanism is represented by the conference reported here, itself an experiment in bringing together representatives of federal agencies, of private and public medical institutions, of industry, and of NASA. Chapters by Ames Research Center staff indicate but a fragment of the Center's potential contributions to the problems of the neurologically handicapped and do not cover any of the relevant work being conducted in several other NASA centers. In spite of this limitation, we in NASA hope that this conference will prove to be a worthwhile experiment, and that it will become a model for future meetings to promote the interchange of medical and engineering concepts for the benefit of people everywhere.

Chapter 3

HEW AND THE NEUROLOGICALLY HANDICAPPED

Warren V. Huber
Associate Director, Collaborative and Field Research
National Institutes of Health

Here we consider some of the neurological disorders with which the Department of Health, Education, and Welfare (HEW) is most concerned. First, however, I shall describe the organization of the Department, because it is a rather complex one with many different agencies involved.

ORGANIZATION AND SCOPE OF HEW

Figure 3-1 shows the general makeup of HEW. Within HEW, the Food and Drug Administration, the Health Services and Mental Health Administration, and the National Institutes of Health (NIH) are considered parts of the Public Health Service and are administered through the office of the Assistant Secretary for Health and Scientific Affairs. The other agencies are the Social and Rehabilitation Service (SRS), the Social Security Administration, and the Office of Education. Three federally aided corporations – Gallaudet College for the Deaf, the American Printing House for the Blind, and Howard University – receive their support through the Office of Education.

Figure 3-2 shows the organization of the National Institutes of Health, the medical research arm of HEW, which includes ten institutes, the Bureau of Health Manpower Education, seven research and service divisions (including one called Computer Research and Technology), and the National Library of Medicine.

A particularly relevant activity of the National Library of Medicine is the Lister Hill National Center for Biomedical Communications, whose mission is to apply communications technology to medical education and to the continuing education of health professionals, and to speed the flow of new knowledge so as to rapidly improve medical care. The Lister Hill Center is engaged in the development of networks and information systems to improve health education, medical research, and the delivery of health services. It also serves as the focal point in HEW for the development and coordination of biomedical communication systems and network projects. The Lister Hill Center is also actively experimenting with the use of communications satellites for medical communications.

The National Library of Medicine maintains a computer-based citation retrieval system through which medical institutions around the country have on-line access to the vast stores of bibliographic citations in the Library's data base.

The federal government's estimated expenditures in the health field in the fiscal year 1971 amounted to about $20.7 billion (Fig. 3-3). Most of this money was spent by HEW, but the Department of Defense, the Veterans Administration, and other federal agencies, expended substantial sums as well. Health care accounts for most of the total, with about $1.7 billion going to support medical research and development. The government supplied 64 percent of the total funds spent on medical research and development in the United States, and NIH accounted for 54 percent of all the federal money (Fig. 3-4) in this area.

A few years ago, the Health Services and Mental Health Administration (which emphasizes the delivery of health care) undertook a national health survey in collaboration with the Bureau of Census. Table 3-1 indicates the scope of the problem as it was reported. During the period under review, 8.5 million

Americans were suffering from some sort of hearing impairment, and over 5.7 million were visually impaired. Over 1.5 million were completely or partially paralyzed. Stroke was the most frequent of the determinable causes of paralysis in this survey. Stroke also was the basic cause of disability in 11 percent of the 1.3 million Americans with speech handicaps.

TABLE 3-1

INCIDENCE OF SELECTED IMPAIRMENTS IN THE UNITED STATES

Etiologies of Impairments (When Known)	Number	Percent of Total
Hearing Impairments (total 8,549,000)		
infection	1,751,000	*20.5%*
injury	652,000	*7.6*
other	2,956,000	*34.6*
Visual Impairments (total 5,717,000)		
local eye diseases (cataract, etc.)	2,662,000	*46.5*
general diseases	322,000	*5.6*
injury	914,000	*16.0*
congenital or birth factors	279,000	*4.9*
other	522,000	*9.1*
Paralysis (total 1,516,000)		
poliomyelitis	451,000	*29.7*
CNS vascular lesions (stroke)	519,000	*34.2*
injury	140,000	*9.2*
congenital or birth factors	171,000	*11.3*
other	125,000	*8.2*
Speech Defects (total 1,298,000)		
CNS vascular lesions (stroke)	144,000	*11.1*
congenital or birth factors	119,000	*9.2*
other	628,000	*48.4*

Source: *Prevalence of Selected Impairments, United States, July 1963–June 1965,* National Center for Health Statistics, U. S. Department of Health, Education, and Welfare.

The distribution of HEW funds in support of various neurological disabilities is shown in Table 3-2. Aside from mental retardation, the neurological handicaps currently receiving the greatest support emphasis from the Department are hearing, speech, and language disabilities. The causes of this group of communicative handicaps are varied. They may be disorders of the ears, defects in the vocal mechanisms, disturbances of the central nervous system that disrupt the input or output of neural impulses or their integration (even though the peripheral mechanisms are unimpaired), or the result of a combination of causes.

TABLE 3-2

DHEW SUPPORT IN NEUROLOGICAL DISABILITIES

Estimated Obligations, FY 1972

Hearing and Speech		
Office of Education	$55,134,500	
Social and Rehabilitation Service	34,767,000	
Special Institutions (Office of the Secretary)	22,047,000	
National Institutes of Health	7,765,000	
Health Services and Mental Health Administration	3,097,000	
Subtotal		$122,810,500
Vision		
National Eye Institute		32,639,000
Cerebral Palsy		
National Institutes of Health	$13,356,000	
Social and Rehabilitation Service	5,000,000	
Subtotal		18,356,000
Stroke		
National Institutes of Health	$ 5,975,000	
Health Services and Mental Health Administration	5,200,000	
Subtotal		11,175,000
Muscular Disorders		
National Institute of Health	$ 5,337,000	
Social and Rehabilitation Service	1,000,000	
Subtotal		6,337,000
Sclerosing Disorders		
National Institutes of Health	$ 3,016,000	
Social and Rehabilitation Service	1,000,000	
Subtotal		4,016,000
Accident and Injury to the Nervous System		
National Institute of Neurological Diseases and Stroke		3,514,000
Epilepsies		
National Institute of Neurological Diseases and Stroke		3,358,000
TOTAL		$202,205,500

The Office of Education supports state programs for educational services for deaf and hard-of-hearing children. Educational research has focused on two major areas: communication problems of the deaf, and the effective use of speech therapists. The Social and Rehabilitation Service maintains a program of training and research in speech pathology, audiology, and rehabilitation of deaf and speech-impaired individuals.

The National Institute of Neurological Dieseases and Stroke endeavors to promote understanding of the fundamental nature of human communication and its disorders through a comprehensive program of research and training. Areas selected to receive special attention are the development of improved sensory aids, the refinement of hearing tests for children, and studies on the effects of noise pollution. The Institute is supporting five multidisciplinary centers in communicative disorders.

The Maternal and Child Health Service of the Health Services and Mental Health Administration stimulates the development and expansion of programs in state health departments and crippled children's agencies for children with speech, hearing, and language disorders. The Service sponsored a national conference this year on selection and cost of hearing aids. Other research activities include two studies to determine the most economical ways of discovering children with hearing impairments. (The National Academy of Sciences has organized a Committee on Hearing, Bioacoustics, and Biomechanics (known as CHABA) to study the problem of hearing. CHABA is supported by several federal organizations, including, indirectly, the National Institute of Neurological Diseases and Stroke.)

AREAS OF RESEARCH

Cerebral Palsy refers to a variety of abnormalities in cerebral control of motor function. As classically used, cerebral palsy implies that (1) the causative event occurred in the prenatal period or in infancy and includes developmental abnormalities, as well as injuries or infections in utero, at birth, and in infancy; and (2) the condition is not progressive. Although symptoms may vary, the two common types are *spastic*, characterized by tense, contracted muscles, and *athetoid*, characterized by involuntary movements of arms and legs.

The National Institute of Neurological Diseases and Stroke is supporting research into the causes of cerebral palsy and methods of prevention and treatment. One example is the Collaborative Project on Cerebral Palsy, Mental Retardation, and Other Neurological and Sensory Disorders of Infancy and Childhood, which is an effort to collect data early in pregnancy from women whose offspring from these pregnancies then are carefully followed both neurologically and psychologically until the age of eight. Data have now been collected on 58,000 pregnancies, and analyses begun to identify diseases and other complications of pregnancy that contribute to brain damage in the offspring.

Recognizing the broad range of handicapping conditions presented by cerebral palsy, the Social and Rehabilitation Service has made extensive use of its various grant programs in the vocational rehabilitation of adults with cerebral palsy and in a special program for severely disabled college students; in the training of rehabilitation personnel; and in the special adaptation of testing methods for the different motor and speech deficiencies involved.

Although the funding information from the Office of Education does not specifically include cerebral palsy per se, many of the programs stemming from the Bureau of Education for the Handicapped are of special relevance. One project of interest is the study of Man-Machine Communications Systems for Disabled Persons. The purpose of this project is to study the feasibility of an interface to allow the severely handicapped to use a typewriter for communication. So far, data have been recorded on slightly fewer than 100 children severely impaired with cerebral palsy; 60 percent were able to make substantial progress.

Stroke ranks third among causes of death in the United States, and frequently incapacitates those it does not kill. It is estimated that there are two million victims of stroke in the United States. The term *stroke* refers to a sudden occurrence of neurological symptoms resulting from interference with or disruption of the blood supply to an area of the brain, the brain stem, or the cerebellum. When brain tissue is deprived of oxygen for more than a few minutes, as when there is not an adequate flow of blood, cells begin to die, and the result is temporary or permanent paralysis of movement, thought, or speech, or an impairment or loss of sensation. The paralysis often involves the upper and lower limbs of one side; this condition is known as *hemiplegia*.

The Department's research and training activities in stroke are centered in the National Institute of Neurological Diseases and Stroke. One of the major programs is the grant support of multidisciplinary clinical centers in 18 universities and hospitals. The Institute plans to establish six acute-care research units involving engineers and physiologists to develop and test systems for monitoring the status of the nervous system and to evaluate new methods of medical and surgical intervention.

On the local and regional level, the Regional Medical Programs service, a part of the Health Services' and Mental Health Administration, has initiated and supported nearly 100 activities in the area of stroke prevention and control, 67 percent of which are in operation. These activities include patient services, demonstrations of the treatment and rehabilitation of stroke victims, assistance in the establishment of stroke intensive care units, and the provision and training of personnel for their maintenance.

The *muscular dystrophies* are a group of inherited muscular disorders characterized by progressive weakening and wasting of the muscles that afflict some 200,000 Americans, primarily children and young adults. Usually the voluntary or skeletal muscles, such as those of the shoulder and hip regions, are affected equally on both sides of the body. Since there is currently no cure, management of muscular difficulties is based on maintaining mobility, building up the less affected muscles, preventing contractures, and treating any acute illness that threatens the patient. Research on other muscular disorders also is under way.

Multiple sclerosis is the most common disease of the nervous system that affects men and women in the prime of life, especially in northern Europe and in North America. This disease afflicts approximately 250,000 in the United States. Its common manifestations are disturbances of vision and balance, as well as partial or total loss of function of the lower limbs. Bladder function is often disturbed. The cause of the disease is not known, and there is no specific treatment. The National Institute of Neurological Diseases and Stroke is now supporting 67 research grants aimed at discovering the etiology of this disorder. The Rehabilitation Services Administration of SRS is placing its emphasis on vocational rehabilitation.

The National Academy of Sciences has called accidental death and disability the "neglected epidemic of modern society." *Trauma* is the leading cause of death in the first half of life's span; in 1965, trauma killed 107,000, temporarily disabled over 10 million, and permanently disabled 400,000 Americans, with injury-associated costs of approximately $18 billion. The nervous system – comprising the brain and spinal cord – is involved to some degree in many of these accidental injuries. The late effects of head injury may include such disorders as epilepsy, paralysis of one or more limbs, and psychiatric and other disturbances. A spinal cord injury may result in permanent loss of function of the lower limbs (*paraplegia*) or of all four of patient's limbs (*quadriplegia*), depending on the location of the injury to the spinal cord.

The National Institute of Neurological Diseases and Stroke is supporting several programs in the study of accident and injury to the nervous system, including nine clinical head injury research centers in universities and hospitals where basic and clinical research is being carried out. Six spinal cord centers are in the planning stage. Animal and physical model experiments are being carried out in a laboratory at NINDS with a goal of understanding the mechanism of trauma to the nervous system, predicting the results of such trauma in man, and establishing the optimum principles of protection, prevention, and treatment.

The *epilepsies* are the subject of considerable work supported by HEW. In one project, electroencephalographic telemetry packs are carried by the patients at home and connected to laboratory computers by radio and telephone lines as a means of collecting precise information on when, where, and under what circumstances epileptic attacks occur, since sometimes a patient is not aware of the fact that he is having these attacks. The number of actual attacks during a day is an important factor in studies of drugs and anticonvulsant medications; one device being considered for development is a seizure counter to be worn by the patient.

It should be emphasized that regardless of the underlying cause, the major neurological disorders are those of locomotion, vision or speech, or hearing and language. The physicians among us are very hopeful that some of the energies of the engineering sciences can be channeled into the areas of diagnostic aids and rehabilitative equipment for the better management of some of these tragic illnesses. We do not expect that the engineer can simply ask a doctor what his problem is and come up with the answer; the technician must work directly on the medical problems in order to understand them. There must be patient involvement, and a close physician-engineer relationship, if rehabilitation engineering, in the terminology of SRS, is to be successful.

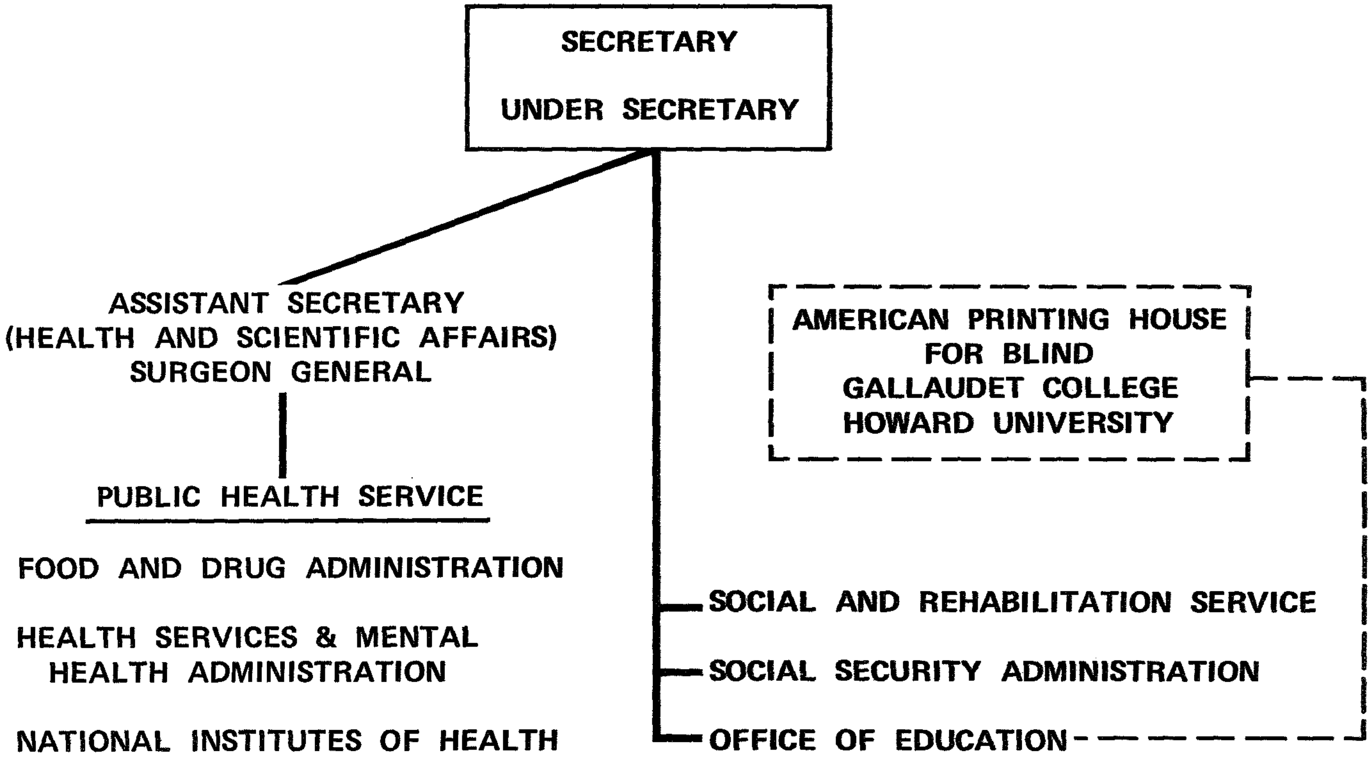


Fig. 3-1.– Department of Health, Education and Welfare.

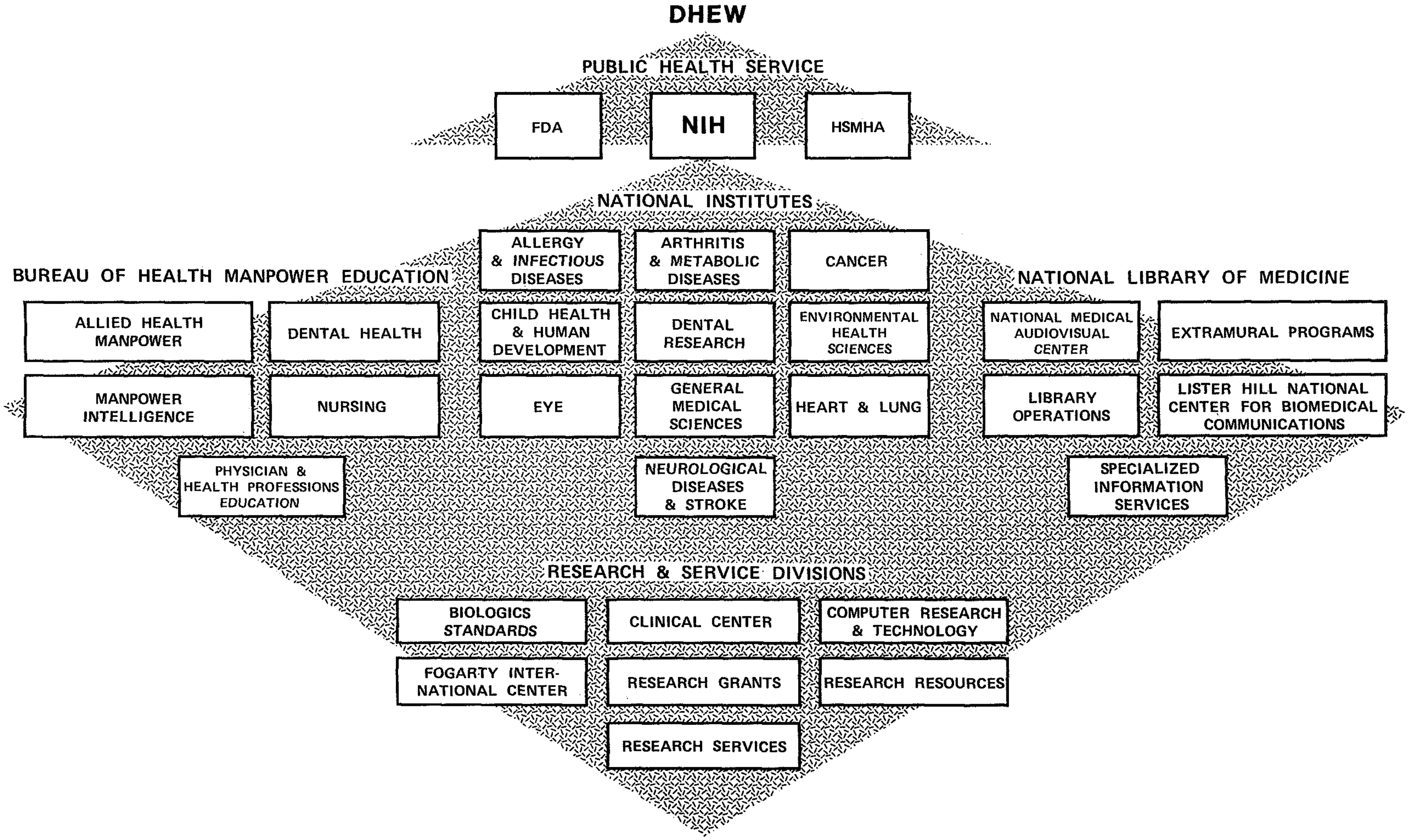
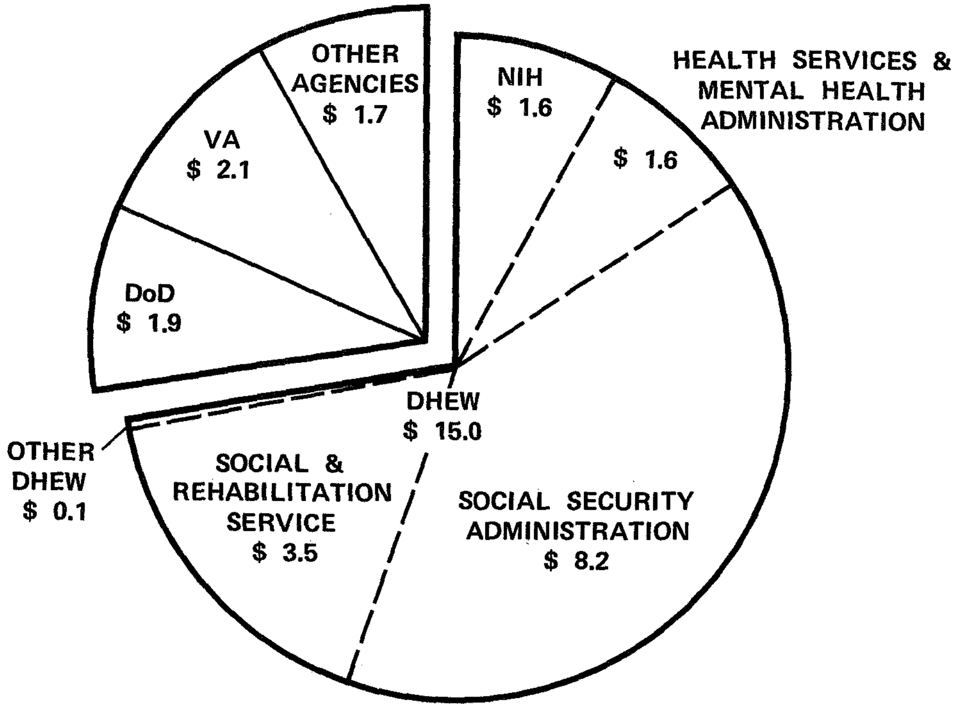
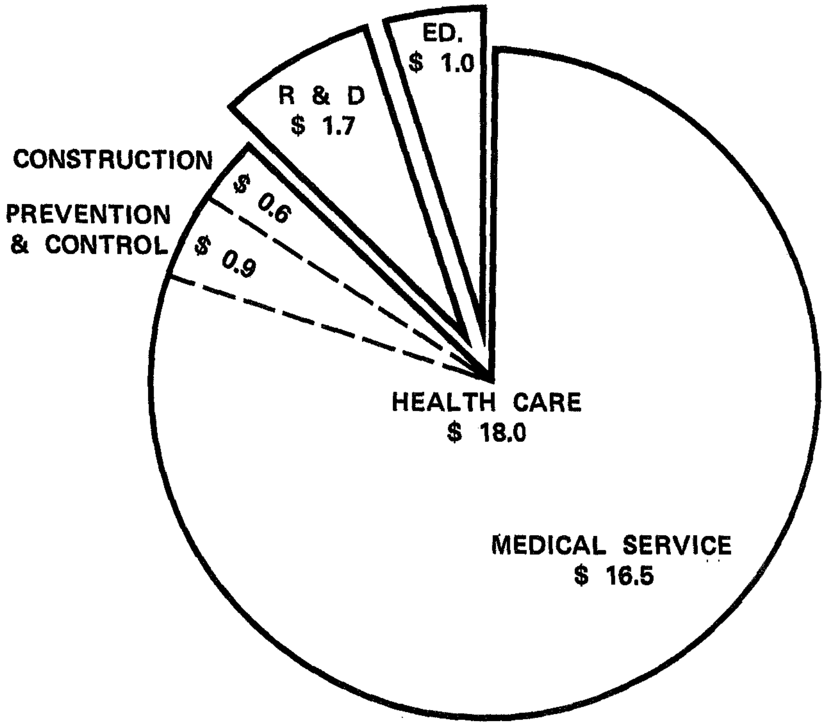


Fig. 3-2.– Organization of the Public Health Service.

BY AGENCY



BY PROGRAM



SOURCE: SPECIAL ANALYSIS, BUDGET OF THE U. S. GOVERNMENT, FY 1972; GPO, 1971.

Fig. 3-3.– Federal health expenditures, $20.7 billion, fiscal year 1971 estimate.

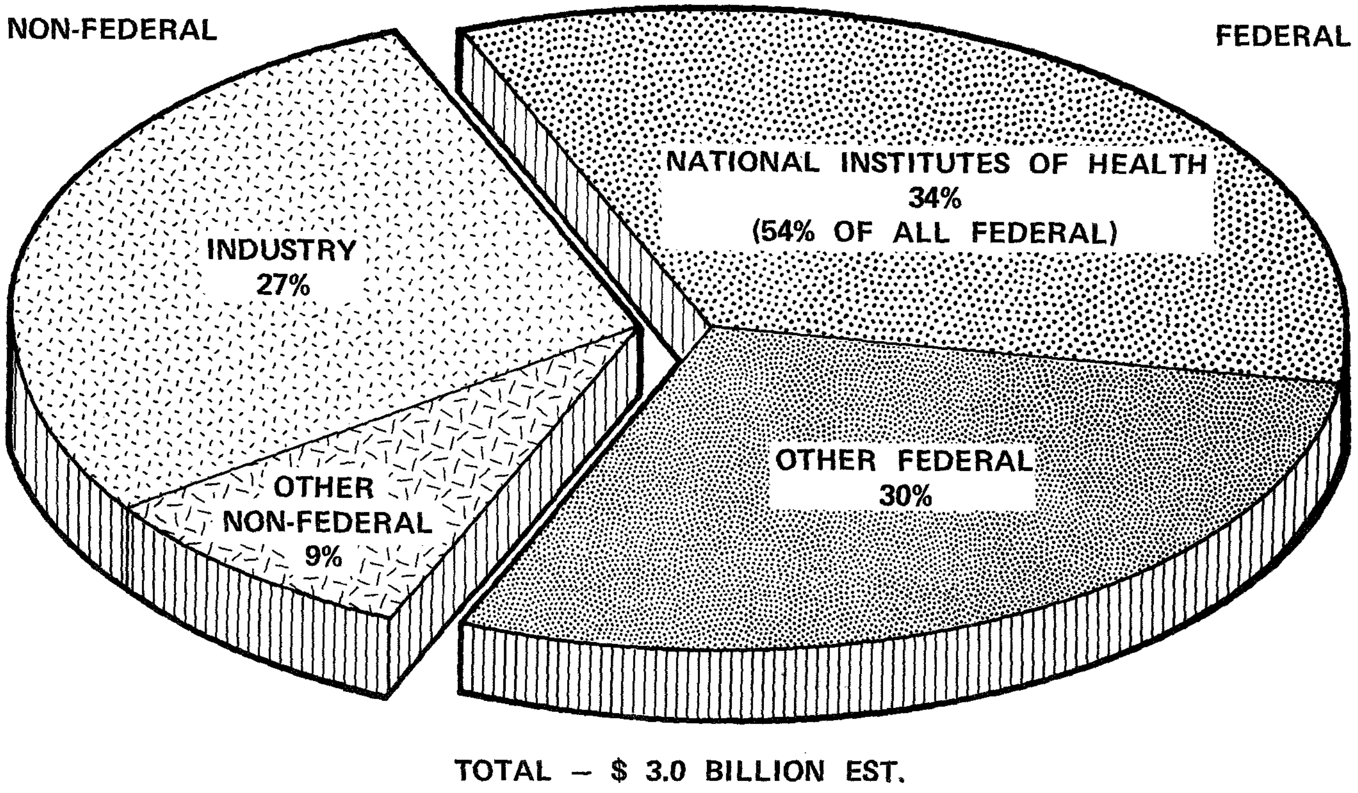


Fig. 3-4.– NIH funds as a proportion of nation's medical R & D 1971 est.

Chapter 4

REHABILITATION AND THE VETERANS' ADMINISTRATION

Franklin Meister
Chief, Neurology Division, VA Central Office

The Veterans' Administration was created by Congress as "an independent establishment in the executive branch of the Government, especially created for or concerned in the administration of laws relating to the relief and other benefits provided by law for veterans, their dependents and their beneficiaries" (Public Law 85-857).

The matter of relief and benefits has a long historical background. Roman legionnaires were awarded public lands, municipal jobs, and, of course, the spoils of war, which were literally the armor and the property of the vanquished soldiers. In the fourteenth and fifteenth centuries, the British and French provided homes for veterans; and the British worked out a rather ingenious device whereby some of the veterans were given an opportunity to work out their own salvation in the form of a beggar's license.

In the United States, soldiers of the Revolutionary War received pensions and land grants from the individual colonies, and later from the federal government. Some 68 million acres were given to veterans of our wars before the procedure was ended on July 1, 1917. Some interesting names appear among the grantees, including Abraham Lincoln, Ulysses S. Grant, Robert E. Lee, Jefferson Davis, and a number of other Americans prominent at the time of the Civil War. After the Civil War, national homes were established for volunteer soldiers and sailors, and these later became parts of what is now the Veterans' Administration.

The historical accounts indicate that the intention to grant benefits and relief to veterans and their families generally was announced early in the period of conflict – apparently to promote enlistments and encourage self-sacrifice in the conflicts. These measures probably were not really honest attempts at rehabilitation, because they never lasted very long after the cessation of hostilities – at least, not until the Veterans' Bureau, forerunner of the VA, was formed in 1921. The Veterans' Bureau grew out of a number of existing organizations, including the Bureau of Pensions, the Bureau of War Risk Insurance (formed about 1914 or 1915 to protect U. S. shippers), and a group of Public Health Service hospitals established to take care of some of our soldiers and sailors following World War I. Around 1918, a subcommittee of the Council of National Defense formulated a framework for the Veterans' Bureau operation, specifying such things as the provision of medical, surgical, and hospital treatment, prosthetic appliances, and vocational rehabilitation for men injured and disabled during military service. These services are a major part of what the Veterans' Administration does today.

During the twenties and thirties the number of veterans decreased. The VA was the subject of considerable criticism, and many were surprised that the Veterans' Administration survived this critical period in its history. Then came World War II and with it a tremendous increase in need.

Today, after 50 years of growth, the VA is the largest operational health care system in the country. It provides about $5.4 billion in pensions and other compensation to some 4.7 million veterans and their families. The agency also provides educational benefits, life insurance and housing loans, and operates 165 hospitals with a total capacity of approximately 90,000 beds, with staffs totaling 150,000 physicians, dentists, nurses, and other health care professionals. Hospital affiliations with 81 medical schools, 51 dental schools, and some 400 universities and colleges provide training for this host of professional and technical personnel. The VA hospitals serve approximately 7 million veterans every year. With recent changes, more ambulatory care is being provided for veterans than before, and the number of eligible people is increasing. A recent public law extends eligibility to all veterans 65 years of age and over regardless of their financial ability to pay.

Over 11,000 medical students acquire a large proportion of their clinical experience in VA hospitals each year, and more than 8500 interns and residents receive most or all of their residency and internship training under the direction of physicians and staff of the VA hospitals and affiliated organizations.

Relatively few veterans needing prosthetic devices and aids are examined by neurologists, and VA capabilities in neurology need to be expanded. In one study, it was found that the number of neurological patients in VA Hospitals on a given day was roughly 7,500. However, a review of the categorical illnesses that should be considered neurological disorders yielded a total on the order of 13,000, which indicates the discrepancy between requirements and the number of neurological units available.

The VA has 118 full-time neurologists, 50 of whom are board certified. There are 65 neurological units among the 165 VA hospitals, and they service approximately 2500 beds. Of the 65 units, 47 are approved for three-year training in neurology in conjunction with the affiliated medical shcool. There are 37 neurosurgical units, with approximately 500 beds and a full-time staff of 18 neurosurgeons, 10 of whom are certified. In addition, many neurosurgical activities are done by part-time people under the supervision and direction of the neurosurgeons in the affiliated medical shcools. The VA Spinal Cord Injury Service has 13 units with some 1100 beds and a total of 44 physicians serving mostly quadriplegic patients, many of whom are severely disabled. The VA also has a considerable research capacity, and many research activities are being conducted by individuals and groups under the providision of cooperative studies.

The Veterans Administration now has an obligation to approximately 28 million veterans who are middle aged or older, and these seem to present an unusual opportunity for investigative study of chronic, progressive neurological disorders. For many of these disorders, we have well-written, well-documented records that go back many, many years. These may not appeal to VA residents of the 1970s, but they are an excellent source of information that is not readily available elsewhere.

The VA work in prosthetic applicances, although initiated at the close of World War I, was not really effective or well-coordinated until World War II began. In the twenties and thirties, as noted, the veteran population decreased. The government obtained some prosthetic appliances through competitive bidding, and others were made by craftsmen in small shops. Under these circumstances, research and development in prosthetic devices could hardly flourish. After World War II, however, the delays inherent in the existing procurement procedures and the increasing need for good quality prosthetic appliances led to a congressional investigation (as periodically happens in the Veterans Administration), and subsequently Public Law 79-268 (Dec. 1945) authorized the VA to provide these appliances through "purchase, manufacture, contract, or in such manner as the Administrator may determine to be proper without regard to other provision of the law" – a very broad authority. This was hardly enough, however, and in 1948, $1 million per year was authorized (Public Law 80-729) for the support of research in the direction of prosthetic applicances and sensory aids. In 1969, the ceiling of $1 million was removed, and funds now can be obtained in the amounts needed to support such a program.

The VA Prosthetic and Sensory Aid Service, centered in the Washington Central Office, supervises all the field activities in prosthetic centers around the country. These centers have prosthetic clinic teams, orthopedic shops, restoration clinics, bioengineering services, orthopedic shoe services, orthotics, and the like. The Research and the Development Division is located in New York City and is independently directed by the chief of the VA Hospital there. The Research and Development Division conducts programs in research, testing, development, education, training, and dissemination of information in the whole field of prosthetics. They use a broad spectrum of approach, and in the development and evaluation, they use pump-priming purchases of expensive early test models. Clinical trials, education, and evaluation of the results is carried out through this organization.

During FY 1970, the prosthetic appliances program served more than 500,000 veterans at a cost of $20 million with an additional $1.6 million for research in prosthesis. By 1980, the cost of the total clinical program is expected to reach $55.8 million, and research costs about $5.8 million.

By tradition and long experience, the VA, under the authorization of a series of public laws enacted by Congress, has achieved an outstanding position in the delivery of health care and in rehabilitation in its broadest sense. Though a great deal has been done, it is safe to assume that the need for prosthetic devices and sensory aids in the VA population will increase. And finally, the VA has many, many patients, it has the machinery, and it has the motivation and the capacity to foster, finance, and conduct sound productive research efforts in the broad field of prosthetic appliances and sensory aids.

Chapter 5

TRANSPORTATION AND THE HANDICAPPED

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For many of our nation's handicapped persons, the unavailability of transportation, either public or private, at a cost they can afford, severely limits their ability to find and hold jobs, obtain regular medical care, further their education, shop in competitively priced markets, and enjoy the everyday social and recreational opportunities available to the rest of the population.

When the community of the handicapped is viewed broadly to include the chronically and acutely disabled, the aged, and abnormally sized persons, it encompasses 33 million people – a surprising fraction of the national population. Improved mobility of this group of people should have many economic, social, and human benefits.

The Department of Transportation is firmly committed to actions that will stimulate the country to provide for the transportation needs of the handicapped. Secretary Volpe, in the foreword to a recent Department publication, *Travel Barriers*, wrote, "There must be within our society a continuing awareness that transportation for the handicapped is good business, good government and good human decency. . . .I assure you [this work] is only the beginning of our efforts to provide suitable, economical transportation for this nation's handicapped."

In this chapter we consider some statistics on the handicapped in relation to transportation, and some of the major deterrents to travel in our existing systems. Some of the benefits of enhanced mobility are identified and examples are given of minimizing travel barriers. Finally, we outline some of DOT's activities that are directed toward improving transportation for the handicapped.

THE HANDICAPPED COMMUNITY

Who Are They?

Some of the more important actions required in using transportation facilities are:

Wait standing
Go (walk more than one block)
Change level
Reach and grasp
Move in crowds
Identify audio or visual cues
Lift and carry

In this context, the handicapped are those who by reason of injury, disease, malformation, or other disability are unable to perform adequately one or more of these actions and therefore are unable or afraid to use existing transportation facilities. For many of these people, special facilities, services, and aids are essential for even a minimal degree of mobility.

Although data on handicapped persons are difficult to obtain, best estimates have been developed of their numbers, travel habits, and special transportation problems. The National Center for Health Statistics has estimated there are about 6 million people whose mobility is limited by chronic medical conditions. Nearly 5.7 million of these are potential users of transportation. This group is of particular interest here and is probably the population segment whose life style can be most influenced by available transportation. Their ability to use transportation can be enhanced by providing prosthetic devices and other physical aids to individuals and by design and planning of transportation facilities to meet their special needs. This discussion is limited to the latter approach.

In addition to the chronically disabled, there are approximately 4.6 million acutely handicapped and 23 million aged, pregnant, and over- and undersized persons whose mobility is severely limited. Thus, in total, more than 15 percent of the U. S. population may be classified as handicapped with respect to transportation.

The Chronically Handicapped

The chronically handicapped, on the average, travel only half as much as the general population, with the major differences lying in work, social, and recreational trips. The able bodied take 2.5 times more shopping trips. Fifty percent use public transportation to get to work and for 25 percent it is a factor in job choice. They tend to reside near their jobs and to travel at off-peak hours where possible. Travel for the handicapped tends to peak between 9 and 11 A.M. compared with 8 to 9 A.M. for all travelers, indicating a desire to avoid rush hour crowds.

Only 36 percent of the handicapped, aged 17 to 64, are members of the labor force, compared with 71 percent in the able-bodied population. Further, the income of the handicapped is much below that of the general population. For example, a recent survey in Boston showed that 59 percent have incomes below $3000 per year. Individual transportation expenses of the same group, however, were relatively high – $5.40 per week or $1.37 per round trip.

TRAVEL BARRIERS FOR THE HANDICAPPED

Obstacles and deterrents that make travel by the handicapped difficult or impossible include architectural barriers (stairs, doors, turnstiles, etc.), fear of injury, inconvenient routes, poor information access, and difficulty of transfer.

The specifications of the American Standards Association for making buildings and facilities accessible to and usable by the physically handicapped are equally applicable to transportation terminals. However, movement-related barriers present an overlay of additional problems. Sixty-one percent of the handicapped are fearful of crowd movement. More than half cannot maintain balance in an accelerating vehicle or ride standing using typical hand grips. Almost 50 percent cannot cross a street in the time cycle of a pedestrian light or negotiate bus or train steps; 20 to 37 percent cannot walk to a restroom in a moving vehicle.

By 1985, nearly 5.2 million chronically disabled will be unable to use existing steps, stairs, or inclines in public transportation; 2.4 million will be unable to open vehicle doors, lift baggage, grasp support rails, or handle small change. Difficulty in sitting and rising in a moving vehicle will be experienced by 3.7 million, and at least 1 million will be unable to identify audio or visual cues.

Planning and modifications of new and existing transportation facilities must receive attention now if better access for the handicapped is to be achieved in the future.

DESIGN FEATURES TO ACCOMMODATE THE HANDICAPPED

Several factors appear responsible for travel barriers to the handicapped: a lack of knowledge of the special needs and problems of the handicapped population, lack of incentives for equipment manufacturers to provide for the handicapped traveler, a belief that the numbers of potential travelers are too small to justify the cost of special design features and facilities, and perhaps most importantly a failure to educate the public and the planners of transportation facilities that barrier-free systems are a matter of *public responsibility*.

The potential benefits of barrier-free transportation, even the direct economic effects, are difficult to assess. In a statistical sample, 30 percent of the chronically handicapped looking for jobs identified transportation as a major factor in their unemployment, and 70 percent of this group would return to work if transportation were available (about 200,000 persons). The minimum benefits (total increase of goods and services) would be about $824 million, not including increased tax revenues, reduced welfare payments, the influence of improved availability of training, or the social benefits. Nor does it include the effects of increased utilization of the same facilities by the (much larger) nonchronically handicapped sector.

Travel Barriers gives some typical improvements and modifications of public transportation that would enhance the mobility of the handicapped; these include (Figs. 5-1 through 5-8):

- Inclinators or elevators for level change
- Lift installation in existing station
- Fare collection gates to replace turnstiles
- Routing information: audio, visual, and tactile cues
- Waiting shelter featuring high visibility, wheelchair space, infrared heating, splash protection, and route information
- In-terminal transportation
- Advanced concept bus featuring wider doors, lower floor, better ride quality, space for wheelchairs
- Powered lift functioning as step and platform.

Features such as these can make conventional public transportation more accessible to the handicapped. Two attractive alternatives involve special dedicated transportation systems for the disabled: a dynamically routed minibus service (dial-a-ride) or the use of special public equipment (such as school buses) during off-peak hours.

ACTIVITIES OF THE U.S. DEPARTMENT OF TRANSPORTATION

DOT is a federation of modal administrations (urban, rail, highway, aviation, etc.) under the leadership of a secretarial office. The Department has completed or has underway a variety of activities, both within the individual modes and in the Office of the Secretary, and directed toward improving transportation for the handicapped as well as the young, the aged, and the disadvantaged. The more important activities include:

- Completion of a study of the transportation needs of the physically handicapped and preparation of design and operating guidelines.
- The passage of the Urban Mass Transportation Assistance Act of 1970, which authorizes $3.1 billion over five years for improved mass transportation. The so-called Biaggi Amendment states that 1.5 percent of these funds *may* be used for the benefit of the handicapped and the elderly. The law states: "It is hereby declared to be the National Policy that elderly and handicapped persons have the same right as other persons to utilize mass transportation facilities and services. . . ."
- Virtually all of the development programs conducted by the Urban Mass Transportation Administration will increase mobility of the handicapped; e.g., demand responsive bus systems, automated personal rapid transit, advanced bus technology, improved vehicle ride comfort, and encouragement of local planners to provide for the handicapped in new urban systems.
- The Federal Highway Administration has prepared and distributed to the States guidelines for the design of highway rest, recreation and sanitary areas to accommodate the handicapped, and has sponsored and participated in a variety of studies dealing with transportation for those unable to drive automobiles.
- The National Highway Traffic Safety Administration has conducted studies and established regulations that will make automotive vehicles easier to control (e.g., force requirements for braking and steering). New regulations for bus emergency egress will recognize the problems of the handicapped.
- The Federal Aviation Administration has prepared an Advisory Circular describing features to be incorporated in new or modified terminals for the 10,000 FAA supervised airports.

These activities are only a beginning toward the solution of an important social problem. The growing national concern for the handicapped and signs of commitment to action are encouraging. This conference and the participation and interest of aerospace and military organizations too are encouraging. But it is clear that federal governmental action alone is insufficient to ensure adequate transportation for the handicapped. Solution of this difficult and important problem will require the combined resources of federal and local government, industry, university, and private institutions.

REFERENCES

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A bibliography of selected references "Transportation for the Handicapped" (lists 195 publications) is available from the Department of Transportation, Office of Administrative Operations, Library Services Division, Washington, D. C. 20590, Nov. 1969.

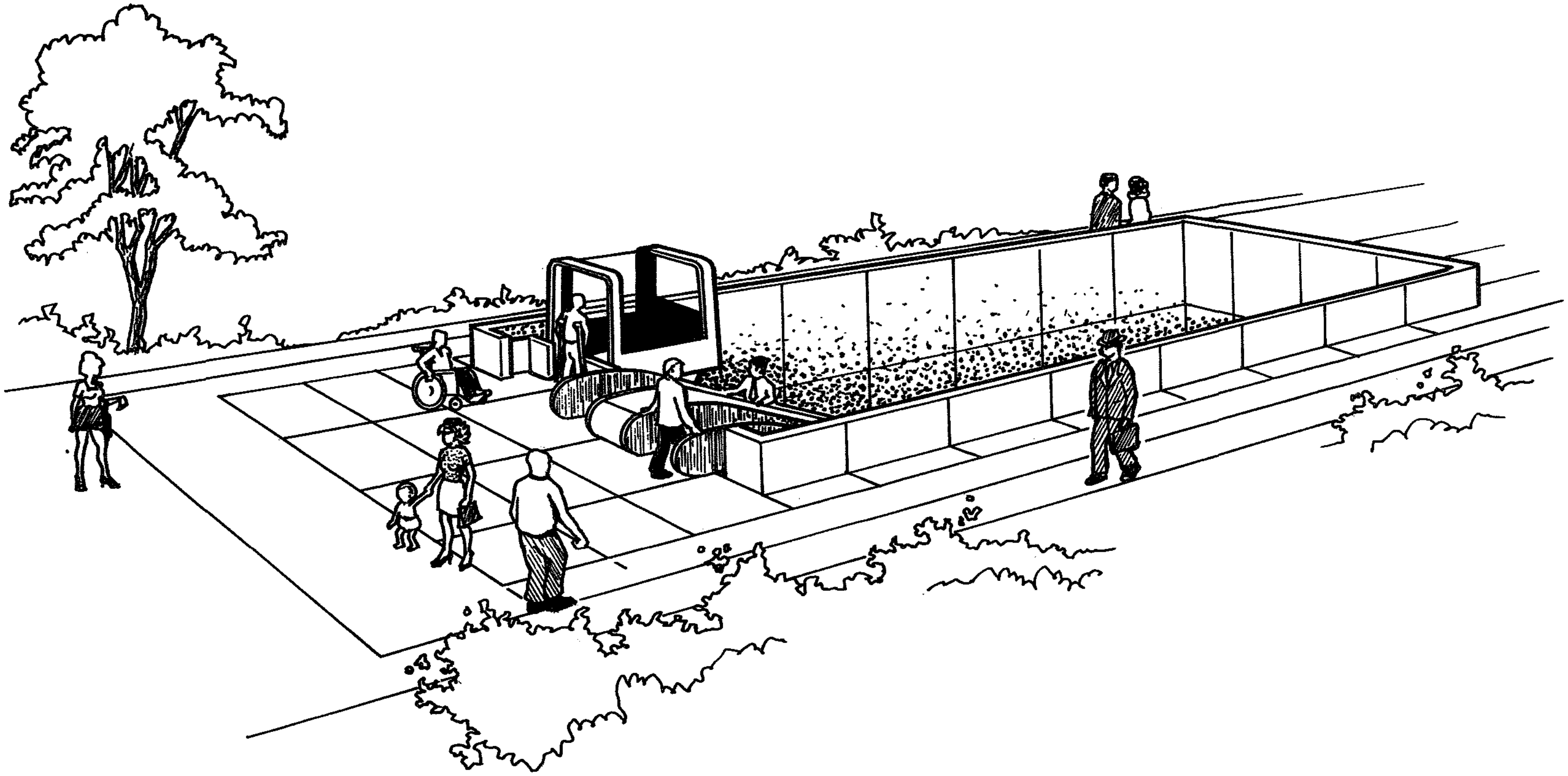

Fig. 5-1.– Inclinators or elevators for changes in level.

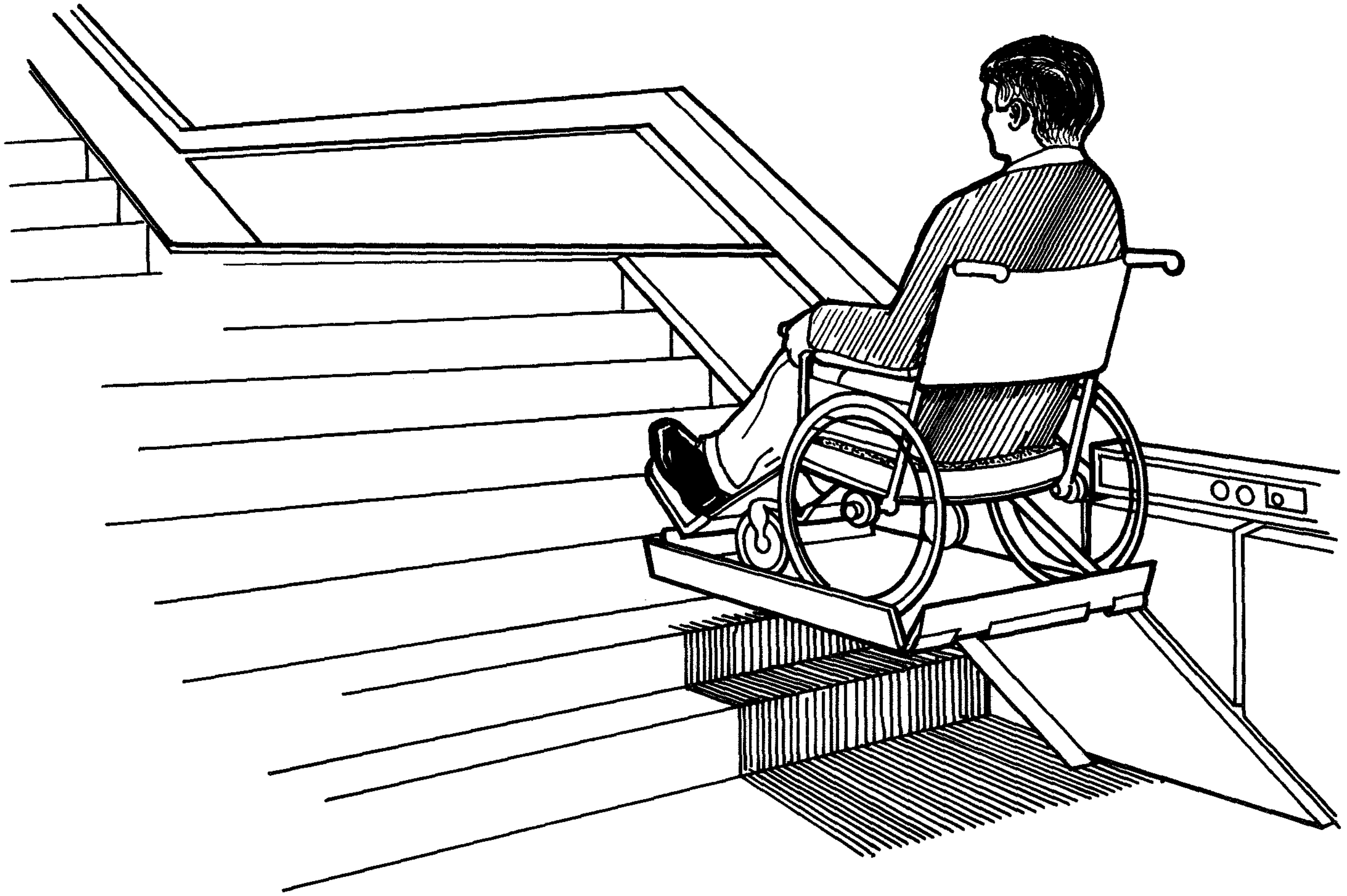

Fig. 5-2.– Powered lift installed in existing station stairs.

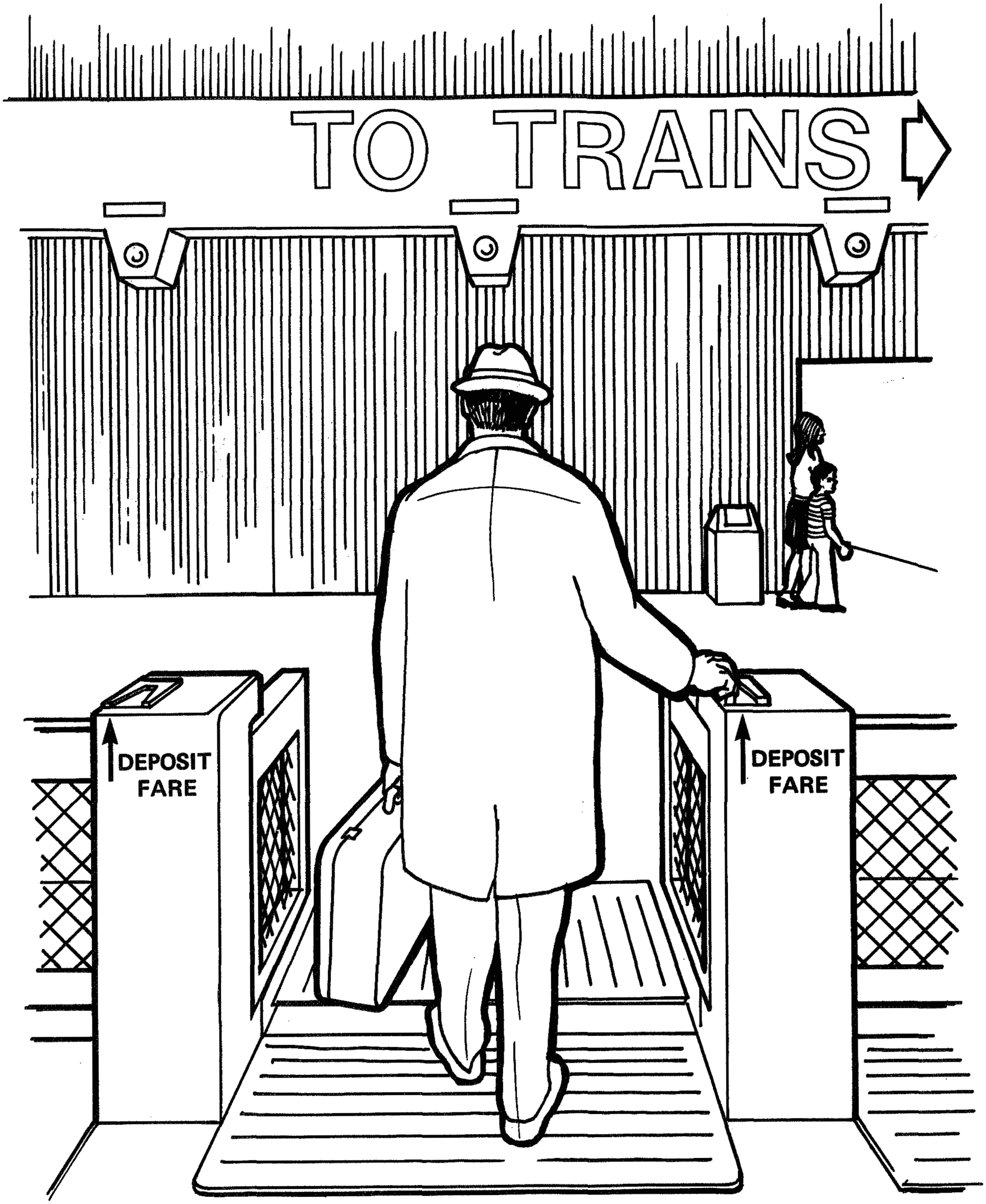

Fig. 5-3.– Fare collection gates (replace turnstiles).

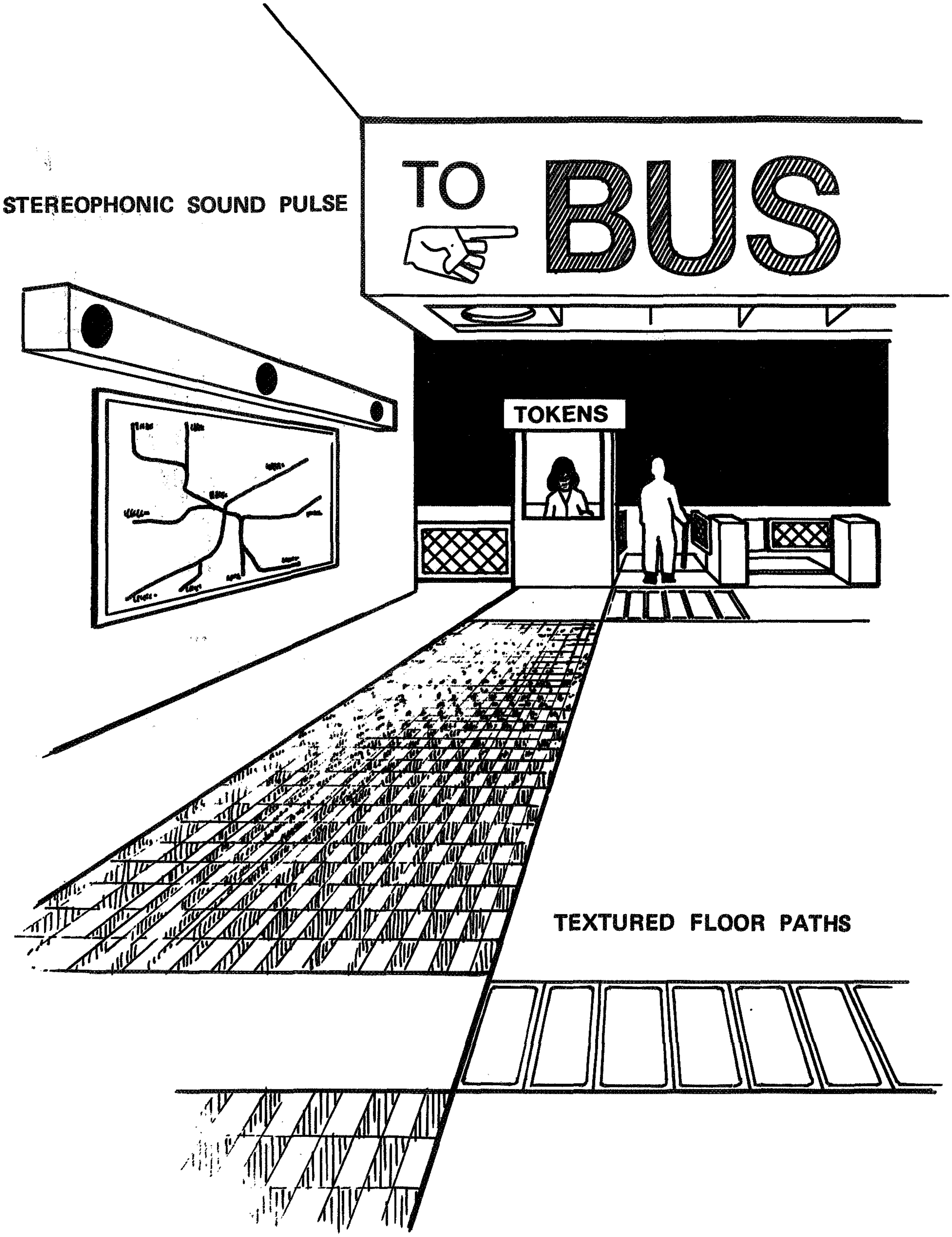

Fig. 5-4.– Audio, visual, and tactile cues as routing information.

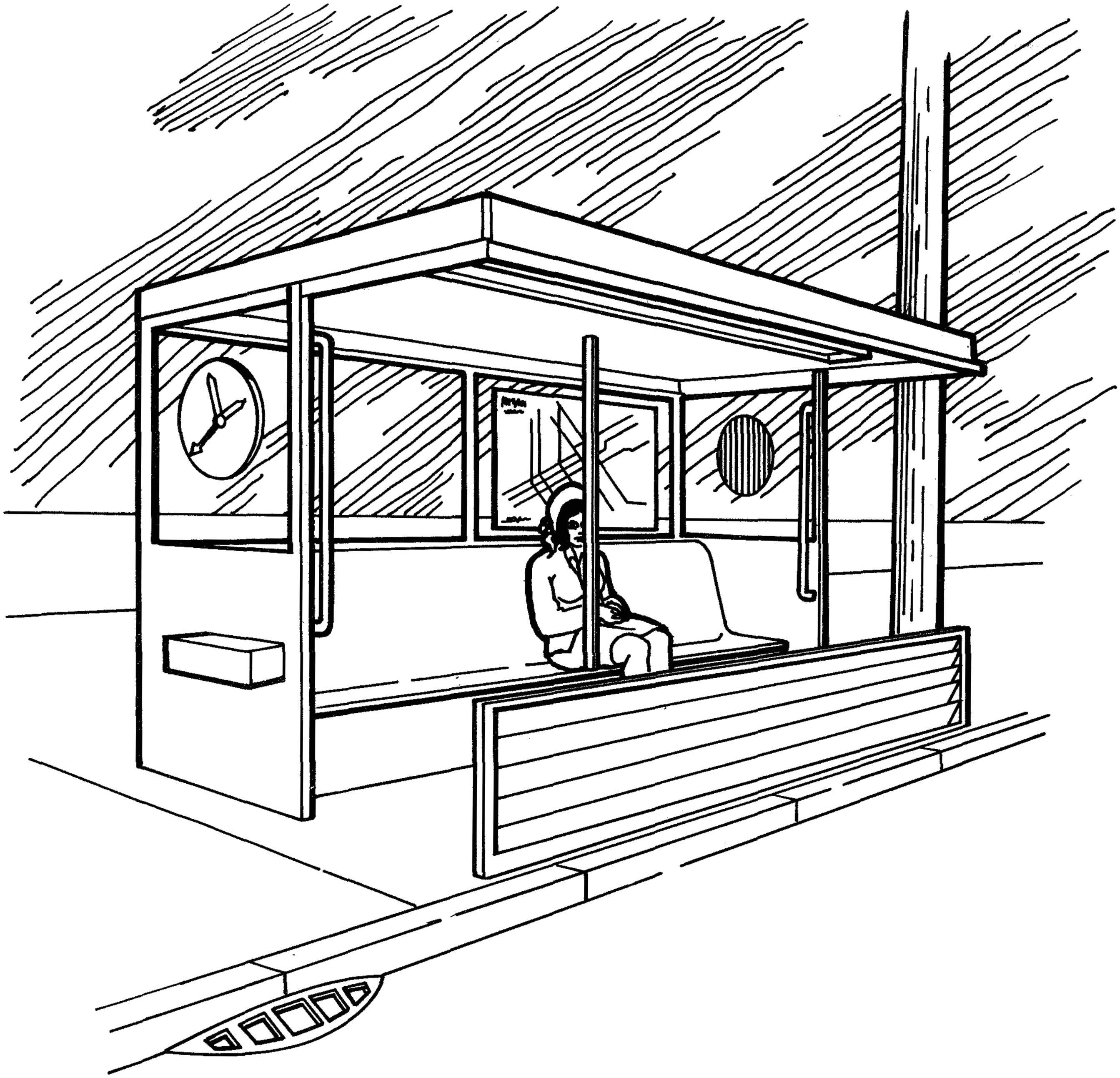

Fig. 5-5.– Waiting shelters at bus stops.

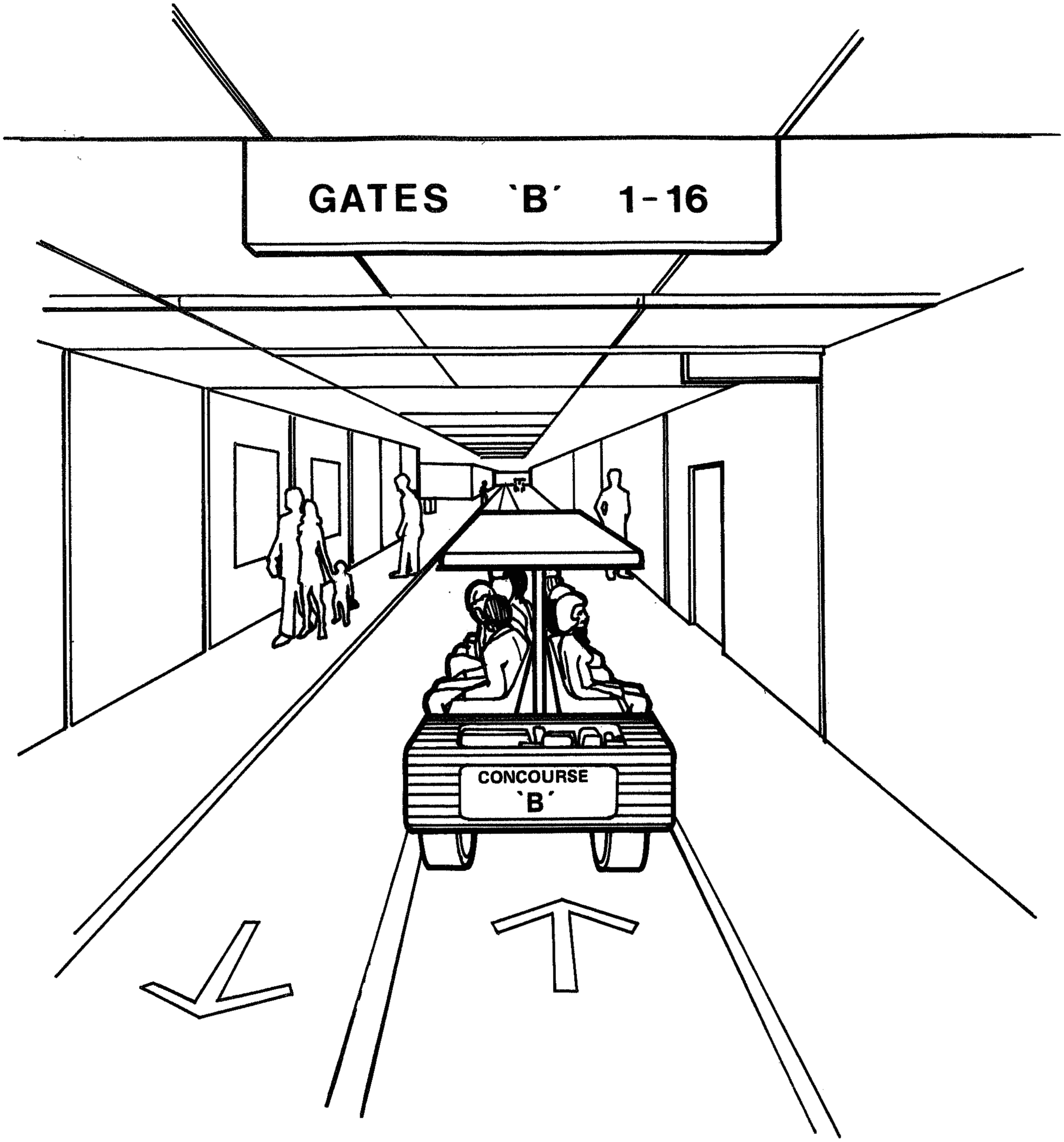

Fig. 5-6.– Electric interior bus in terminal.

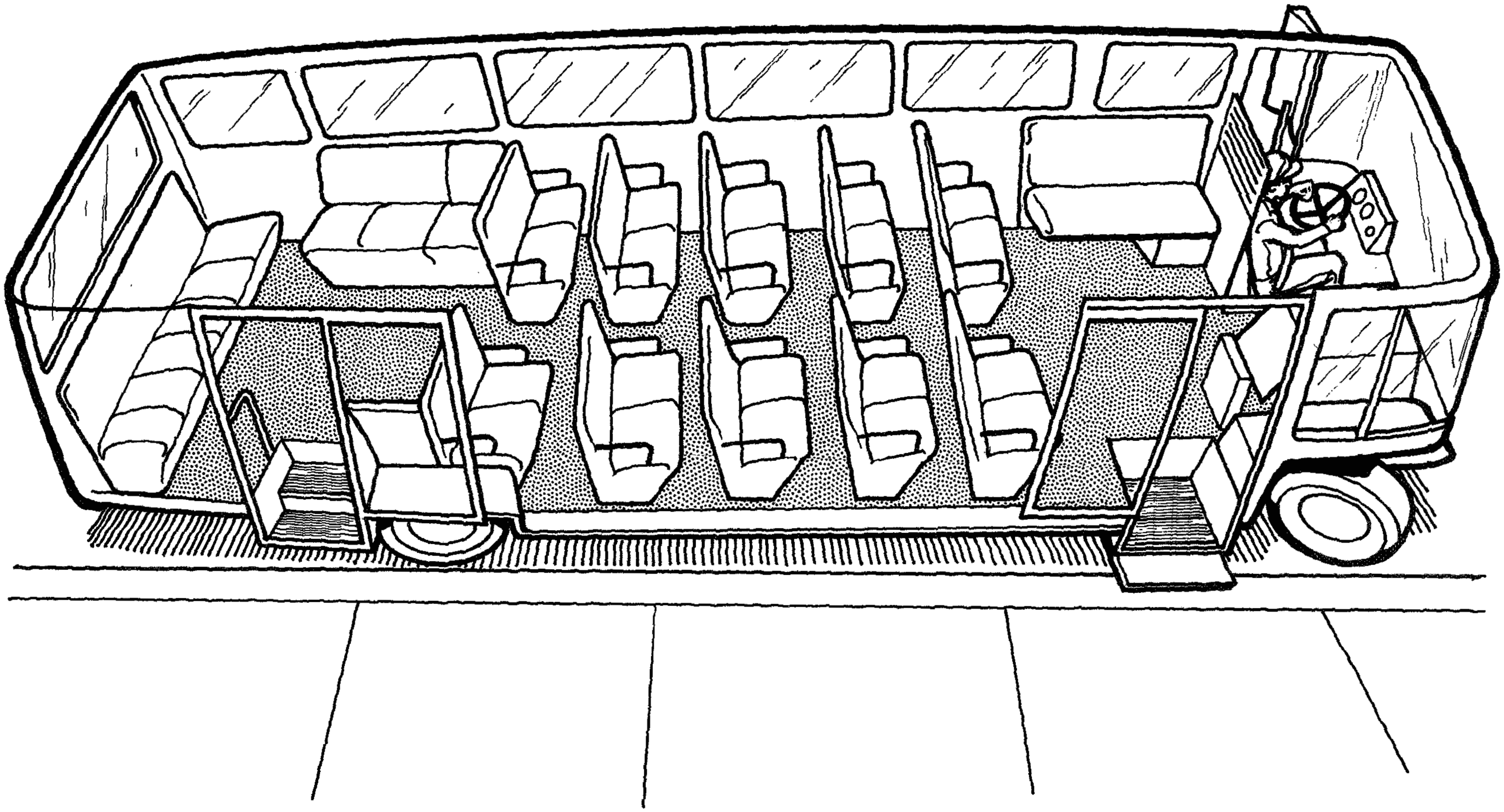

Fig. 5-7.– Advanced concept bus.

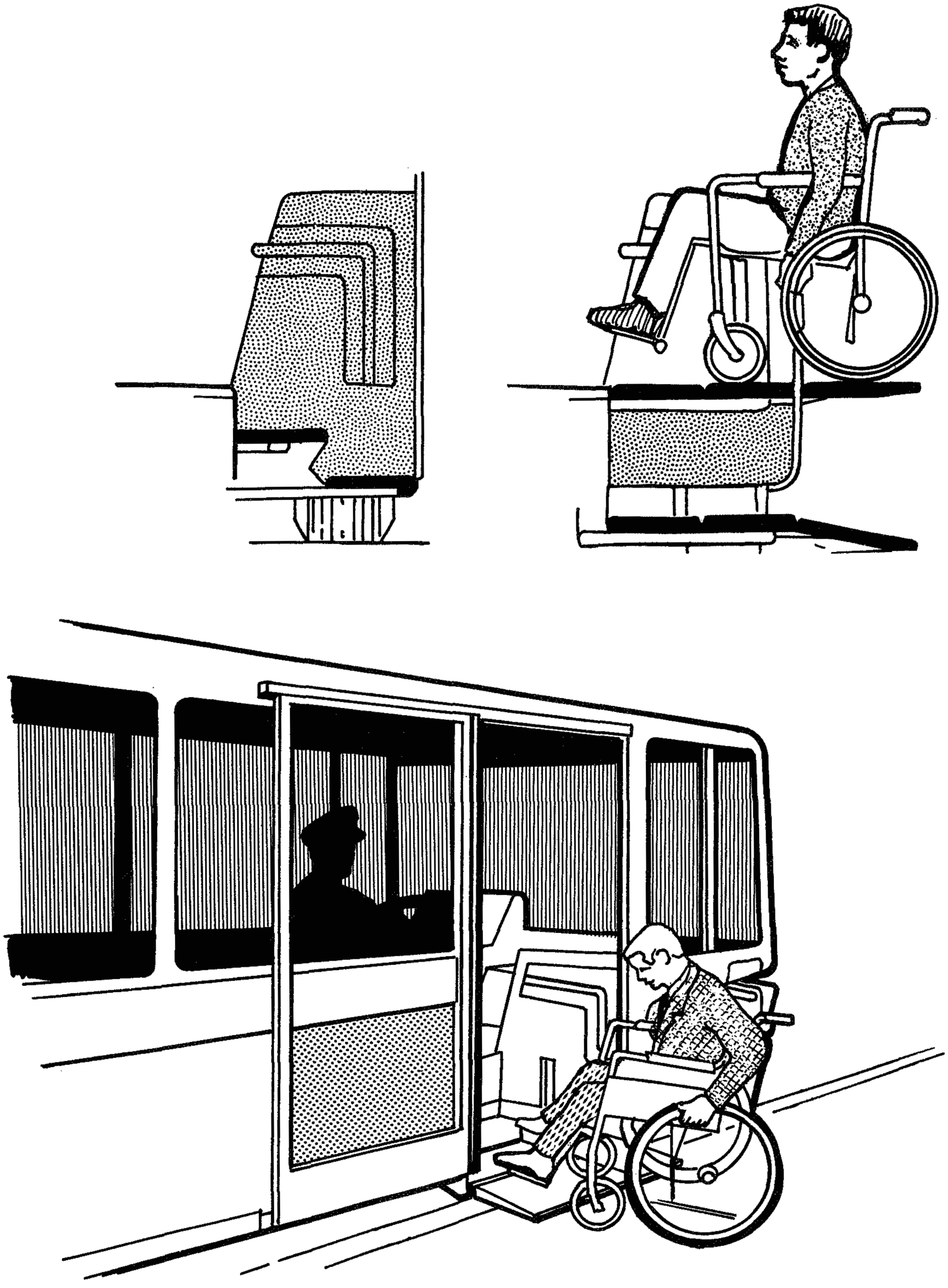

Fig. 5-8.– Powered lift as step and platform.

Chapter 6

THE NATIONAL RESEARCH COUNCIL PROGRAM ON AID TO THE NEUROLOGICALLY HANDICAPPED

Colin McLaurin
Chairman, Committee on Prosthetics Research and Development
National Academy of Sciences

The National Academy of Sciences was founded in 1863, at the time of the Civil War. A relevant portion of the founding act reads:

> And it be further enacted that the Academy shall whenever called upon by any department of the government, investigate, examine, experiment and report upon any subject of science or art, the actual expense of such investigations, examinations, experiments and reports to be paid from appropriations which may be made for that purpose, but the Academy shall receive no compensation whatever for any services to the Government of the United States.

After over a hundred years, the Academy still can accept no fees for the work it does for the government, but the government pays the expenses.

Academy participants met at the Smithsonian Institute until 1922, when the present building on Constitution Avenue was built through private gifts (all subsequent Academy facilities have been funded privately).

From an initial staff of about 50 people, there are now about 800 scientists and engineers in the Academy of Sciences. The National Research Council, established in the 1940s, is essentially the executive arm of the Academy, and it has increased the Academy's effectiveness significantly. The Academy now has a salaried staff and a total of about 7,000 scientists and engineers, 400 committees, and 150 scientific societies are represented.

In 1964, the National Academy of Engineering was established, essentially as a sister Academy, but under the corporate body of the National Academy of Sciences. The National Research Council is the executive body for both.

The National Research Council has nine divisions, three of which are involved in activities pertaining to the subjects under discussion here. The Division of Behavioral Sciences has a Committee on Hearing, Bioacoustics, and Biomechanics. The Division of Engineering has two associated committees: The U. S. National Committee on Engineering in Medicine and Biology, set up to work with other groups on an international level, and the Committee on Prosthetics Research and Development (CPRD), which is actively engaged in this area. The Division of Medical Sciences has a Committee on Brain Sciences. The Committee on Prosthetics and Orthotic Education (CPOE), which works very closely with CPRD, disseminates much of the information developed in the research programs.

The Committee on Prosthetics Research and Development was established in 1945, largely in response to the requirements of veterans, and it comprises many noted engineers and scientists. Aircraft companies were involved as well; one was Northrup Aviation. An artificial leg and artificial arm was quite simple compared to an aircraft. It appeared obvious that within a year or so all the problems would be solved. Yet over a quarter of a century later, most of these problems are still with us. Some of them have been solved, however, and the Academy can serve an important function in solving others.

It must be remembered that the Academy has essentially no authority, and is basically an advisory group whose services are available to any agency of the government. The agencies which support the work of CPRD are the Veterans Administration, Social and Rehabilitation Services, and Maternal and Child Health Services, the Army and the Navy, and to a lesser degree the National Institutes of Health. Clearly, when two or three government agencies are doing research work in the same area, an independent body can identify areas of overlapping activities and generally take a broader view of progress being achieved. This is an important function of the Academy. Another is coordination of the various activities; one aspect of this function is the organization and conduct of various meetings and seminars with participants from the various programs sponsored by different agencies.

A third Academy function is to disseminate information – through conferences, publications, and periodicals, such as *Artificial Limbs*, and *The Inter Clinic Information Bulletin*, which keeps people up to date on what is going on.

The Committee for Prosthetic Research and Development, in addition to its role as prescribed by the functions outlined above, has a unique commitment to project utility – that is, a continuing interest and participation in a project from its conception to optimum application. It is not enough merely to advise somebody that a project is worthwhile and should be funded. The policy of CPRD is to see it through development, have it evaluated, taught in schools, and then brought to the patient where it can be used. This commitment to utility is one of the enduring features of CPRD, and it appears to be a unique feature within the Academy.

The committee comprises a dozen or so members of various disciplines – typically medicine, engineering, and prosthetics/orthotics – and the members work together very closely. At a CPRD meeting it is difficult to tell who is the doctor, who is the engineer, and who is the limb maker. The members rotate every three years, to keep new blood coming in. The committee has a very competent staff of three professionals and three or four secretaries. Subcommittees include Fundamental Studies, Design and Development, Evaluation, Children's Prosthetic Problems (which includes Orthotics and cerebral palsy), and Sensory Aids. The subcommittees conduct various workshops, panels, and conferences. For example, Fundamental Studies has recently arranged a conference to be held in Houston on the effect of pressure on tissues.

These workshops, conferences, and panels, in which the knowledge of experts in the various fields can be brought together, generate an awareness of current activities and facilitate planning over the longer range as a basis for advising sponsors on new developments.

CPRD is involved in some 70 projects, mostly at universities or at rehabilitations centers throughout the country. The total cost of these projects is on the order of $4 to 5 million annually – a relatively small amount well spent. (The Veterans Administration has shown that their $1.6 million a year in research in prosthetics has paid off rather handsomely: It has not only provided better service to the amputee but it has saved the VA money over the years.) The CPRD program is not restricted to prosthetics; we are deeply involved in orthotics, sensory aids, and recently internal prosthetics, particularly joint replacement.

Of the 70 projects in the CPRD program, about 20 are related to the neurologically disabled, primarily the stroke patient, spinal cord injuries, and other upper extremity or lower extremity bracing (either mechanical or electronic).

There is considerable interest in cerebral palsy, although at present comparatively few projects are under way. Most of this interest stems from a group of clinics, formed to coordinate work for the child amputee. There are some 30 outstanding clinics that serve child amputees in this country, coordinated by a CPRD subcommittee. Recently, most of the committee members have become aware of what can be done for the CP child, and certainly any of the engineers who have worked with braces or limbs, when they see a CP child, their eyes light up and they say, "Well, there is a lot that can be done." There is this awareness.

What can be achieved can be described in terms of enhancing *treatment*, so that the therapy program can be hastened, or in terms of *function*, so that the child can do things that he couldn't do otherwise. Support (how the child is seated), mobility, and communication are areas where technology can contribute.

The communications systems developed by the Cybernetics Research Institute are now being evaluated by CPRD in cooperation with a subcommittee under Behavioral Sciences.

The CPRD program has been oriented toward applied research, rather than long-term basic research. A number of fairly simple and practical devices are under study or have been developed to aid the mobility of the CP child. Incidentally, the cost to keep a child amputee in limbs is something like $200 per year. A similar fee probably could apply to CP, as a general rule, whether the need is for mobility aids or communication aids. We will discuss a few examples here.

Consider the handicapped child who can crawl a bit, but cannot walk or manage his own wheelchair because his arms are involved as well. We might try a *walker*, which consists of four wheels, is steerable, and has a bicycle seat. The child can get around on his own – he does not have to wait for somebody to push him. At the same time, the walker generates the kind of motion that will probably help him walk later on if he does acquire this ability.

With another wheeled device the child gets around by pedaling. The child's ability to pedal was discovered by examining myoelectric signals, where a repetitive pattern was observed in the leg muscle records.

An older child who would not want to get around on a tricycle might use a *modified wheelchair*, which has been fitted with pedals. Steering is achieved with a tiller, thus allowing mobility for the child who is unable to operate the wheelchair with his hands.

Chapter 7

NEURAL CONTROL: LONG-RANGE PROSPECTS

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OBJECTIVES IN NEURAL CONTROL

In the National Institute of Neurological Diseases and Stroke (NINDS), the Laboratory of Neural Control is a multidisciplinary group with common ojectives that are fundamental to neural control. These objectives are:

1. The development of long-term connections with the nervous system, for direct transfer of information into the nervous system.
2. The development of long-term connections for direct readout of information from the nervous system.
3. The study of basic neurophysiological control mechanisms operating in the nervous system.
4. The investigation of potential applications of such developments. These applications depend strongly on the successful achievement of the first three objectives.
5. The attempt to envision the social consequences of these developments.

INFORMATION TRANSFER AND CONTROL MECHANISMS

If we had a means for discretely and independemtly stimulating neurons or small groups of neurons for long periods of time without undue harm to the rest of the organism, we would be able to transfer information into the nervous system. For example, Nashold is investigating stimulation of the spinal cord for urinary bladder evacuation in paralyzed individuals as well as techniques of nervous system stimulation for relief of chronic pain (Chap. 10). Bliss and his associates have developed a reading aid for the blind that involves stimulation of tactile receptors (Chap. 16). Others are investigating means to control epilepsy and certain psychoses.

The feasibility of a visual prosthesis for the blind utilizing direct stimulation of the central nervous system is being studied by Brindley in England and several groups in the United States. It has been known for some time that electrical stimulation of portions of the brain concerned with vision can produce sensations of light, even in blind people. If such stimulation could be derived from an array of light sensors or a TV camera, a prosthesis for reading and mobility is possible even though an accurate representation of the visual word will be unlikely. Pudenz discusses problems and progress in this area in Chapter 12.

Figure 7-1 shows an implant developed by Brindley for the study of visual sensations produced by electrical stimulation of the visual cortex in humans. This consists of an array of 80 platinum electrodes, placed against the visual cortex, connected by 80 leads to a series of 80 receivers that are potted in medical grade Silastic.

Figure 7-2 is an x-ray of the implant inserted into a blind human volunteer by Lewin (Cambridge University). You can see the electrodes against the visual cortex. The lead passes through a rather small hole in the skull to the 80 individual radio receivers that activate the electrodes. Although this device was entirely experimental and was of no direct benefit to the patient, it answered many questions concerning the feasibility of a visual prosthesis. With this implant, the patient reported that 39 of the 80 electrodes gave highly localized sensations of light, which we call phosphenes, when the current was applied.

In the more distant future, if a visual prosthesis proves feasible, an auditory prosthesis for deaf people unable to use a hearing aid may be possible. This would involve stimulation of an auditory area of the brain to achieve speech recognition through tonatopic localization and temporal sequencing. Another prospect involves supplying feedback information to the central nervous system from artificial limbs. Mann and his group at MIT are investigating stimulation of the peripheral nervous system through skin receptors as a means of transferring information on joint position in artificial limbs (Chap. 13). Similarly, if we had a method of independently and simultaneously determining the activity of neurons or small groups of neurons, we could use such information for the control of external devices. Control of artificial limbs by electrical signals derived from intact muscles is the subject of research in several centers throughout the world. However, the number of independent signals is quite limited, and this in turn limits the number of independent degrees of freedom in the prosthesis.

As an alternative, members of the Laboratory of Neural Control are investigating the possibility of deriving the signals from the motor area of the brain. Figure 7-3 shows recordings of data taken from an unanesthetized monkey with electrodes implanted in its left motor cortex. There are four separate independently adjustable microelectrodes in that area of the cortex. The top trace is of the force output from the right arm during a push-pull movement, which the animal has been trained to perform. You get some idea of the type of signals that can be obtained from the motor cortex during a trained act. It is hoped that we will be able to use these in the future in the control of artificial limbs.

If such an approach becomes practical, many other applications would be worth investigating. Among these are direct control of communications equipment, direct interfacing with computers, and control of teleoperators. The gains in efficiency of communication could be quite significant, since a large part of the motor system could be bypassed.

Combinations of simultaneous inward and outward information flow would be one of the next logical extensions. In individuals suffering from spinal cord injuries, cerebral palsy, or stroke with resultant paralysis or paresis, the affected areas might be effectively bypassed. In a closed-loop system this would involve three major aspects:

1. The derivation of command signals from the brain and sensory signals from the intact sensory receptors in the periphery or hardware transducers.

2. Appropriate processing of these signals.

3. Inward transfer of the processed signals to the sensory areas of the brain and to the intact peripheral motor system.

Preliminary work in this area has already resulted in some applications. For example, Liberson attached a mercury switch to the heel of a patient with footdroop. The switch is closed during a swing phase of the gait, and stimulation is applied to the peroneal nerve resulting in an upward flexion of the foot (Chap. 8). Similarly, C. Long has investigated correction of the "drop wrist," and Dimitrijeric in Yugoslavia is attempting to extend the work to include stimulation of the sensory system as well as the motor system.

Functional activation of muscles by electrical stimulation is not possible in cases where the peripheral nerves to the muscles are damaged, because these muscles atrophy.

PROBLEMS IN NEURAL CONTROL RESEARCH

Starting outside the body and working in, there is a need for percutaneous signal-transmission systems with high packing densities. As implanted devices, these must be doubly biocompatible – they must not be injurious to the host, nor should the host attack the implant. The percutaneous systems might be either high-density hard-wire connectors or noninvasive energy-coupling systems, such as RF multiplex telemetry. A low impedance path must be provided between the site of stimulation or recording and the percutaneous transmission system. This will require high-density flexible leads. Signal processing en route will require appropriate analog or digital microcircuits, often custom designed for the application.

The most difficult problems are those of the "biological-hardware" interface. If we desired a readout device, such as a microelectrode, any relative movement between it and the neuron it is recording from must be kept within strict limits. The present systems also suffer from polarization problems, relatively low signal-to-noise ratios, and unknown damage during insertion. Present techniques for stimulating neurons suffer from many of these problems as well as their own limitations. If metal microelectrodes are used for stimulation, relatively large amounts of power are dissipated at the electrode surface. This results in heat and electrolysis, which are unwanted by-products. Stimulating currents from these electrodes diverge after leaving the tip, which makes focal stimulation of single neurons or small groups of neurons difficult. Ideally, we would like to have a noninvasive stimulating technique that could be focused on the desired neuron population, whose only effect is to transfer ions across the charged cell membrane. In reality, an extension of our present capabilities would be very useful.

In summary, the long-range prospects for neural control depend to a great degree on development of long-term connections with the nervous system. As advances are made in this area, more sophisticated applications will be investigated.

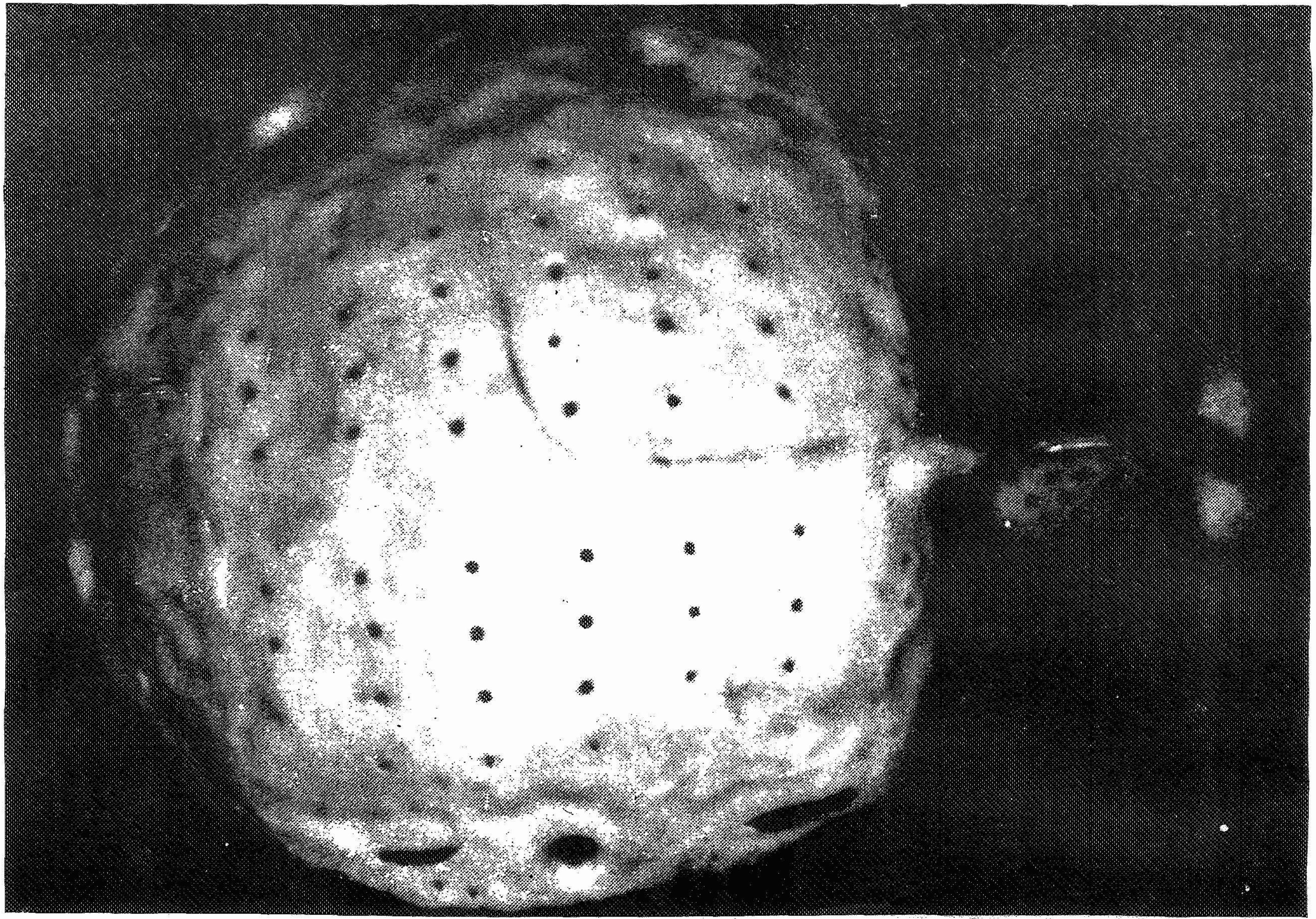

Fig. 7-1.– Implant for the study of visual sensations produced by electrical stimulation of the visual cortex (from Brindley, G. S. and Lewin, W. S.: *J. Physiol.* (London) 196:479, 1968).

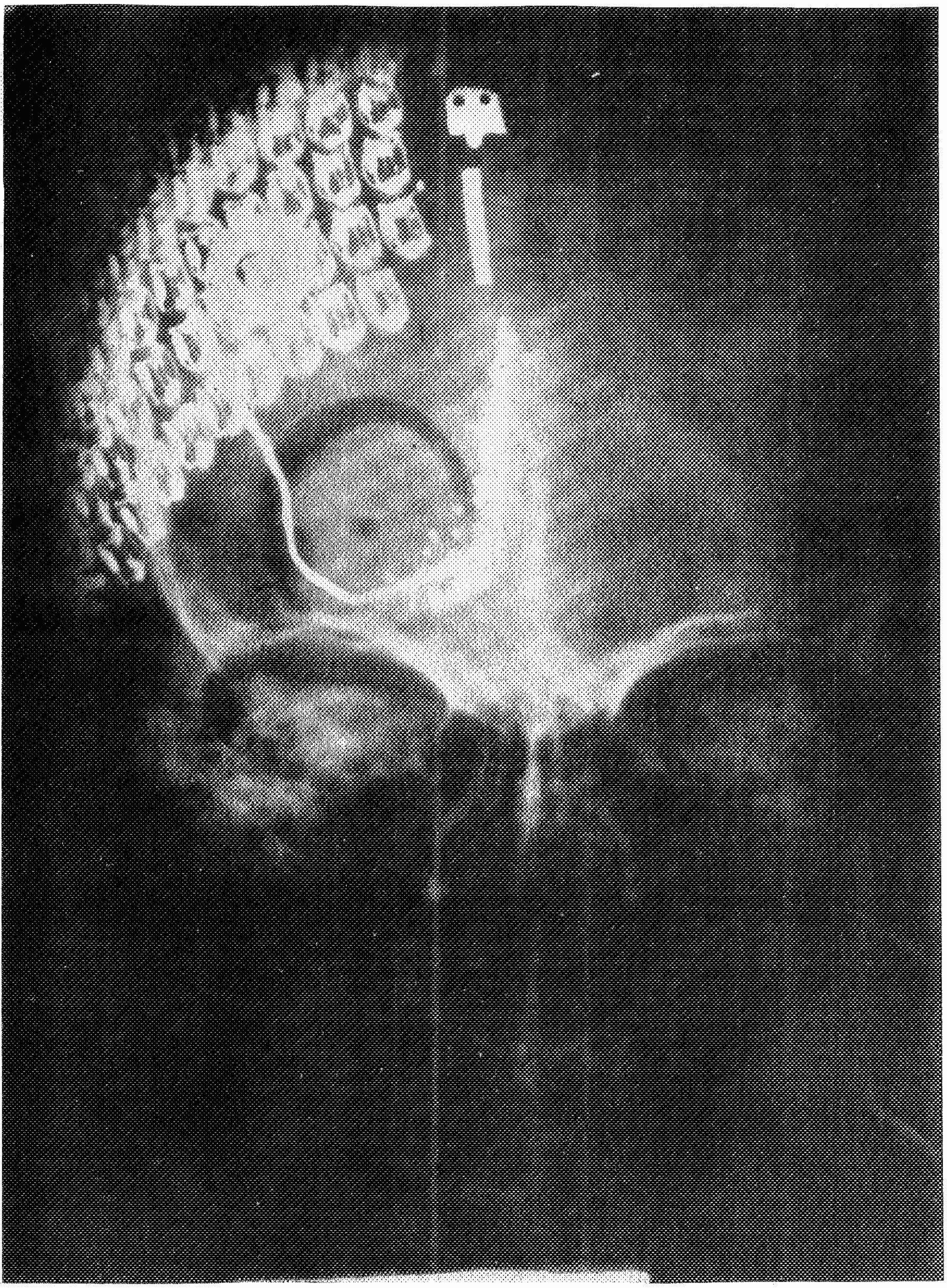

Fig. 7-2.– X-ray of implant in blind human volunteer (from Brindley, G. S. and Lewin, W. S.: *J. Physiol.* (London) 196:479, 1968).

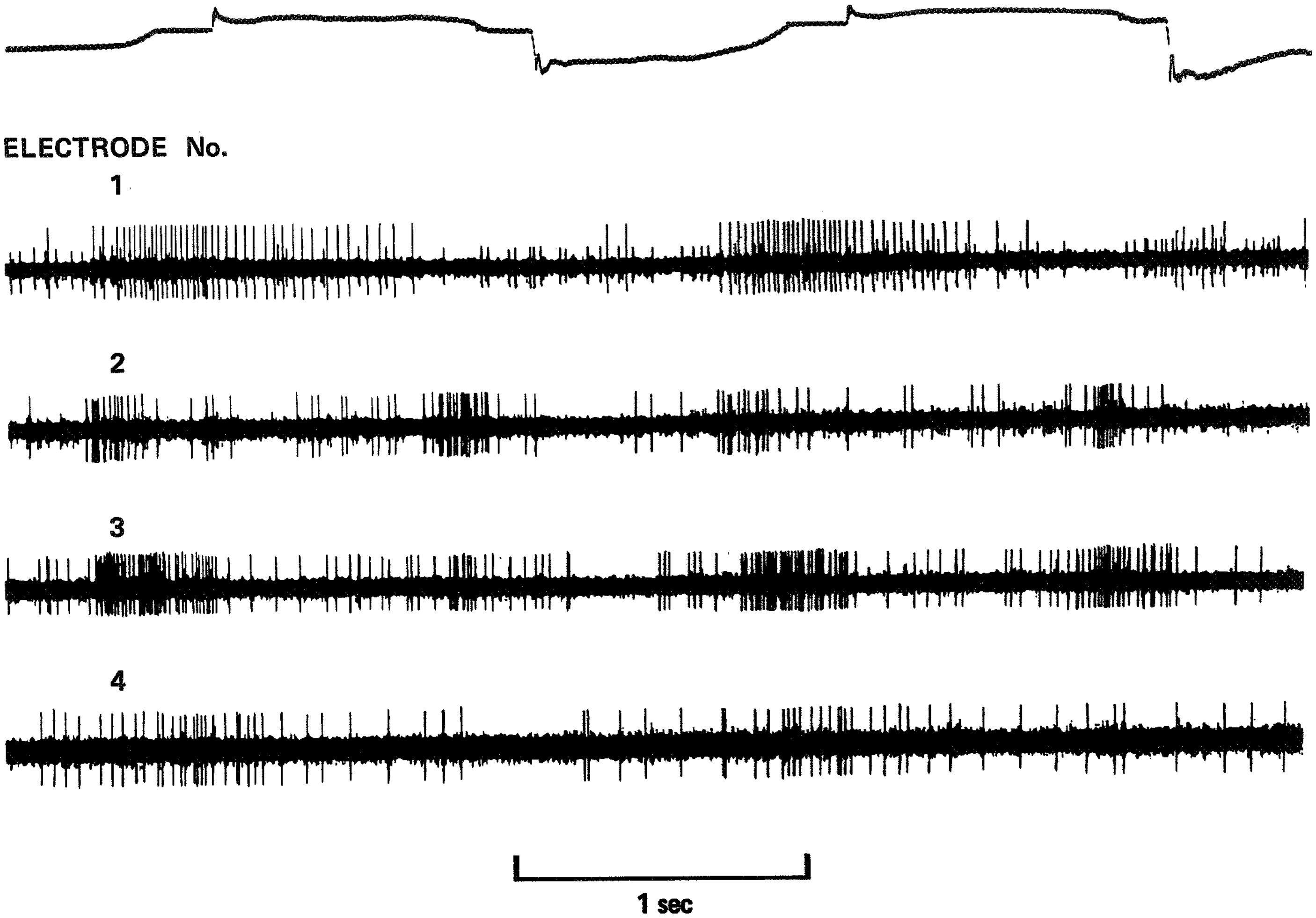

Fig. 7-3.– Traces of motor signals from the motor cortex in an unanesthetized monkey (from Humphrey, D. R.: Electroencephalogr. Clin. Neurophysiol. 29:616-620, 1970).

Chapter 8

CURRENT THERAPEUTIC TECHNIQUES AND REHABILITATION FROM NEUROLOGICAL DISORDERS

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Rancho Los Amigos Hospital is a 1100-bed teaching hospital of the University of Southern California. It is primarily oriented toward rehabilitation. The individual services that deal with neuromuscular disorders are categorically disease entity oriented: they are directed toward the major problems, such as spinal cord injuries, amputations, stroke, cerebral palsy, and rheumatoid arthritis. The services at Rancho cross many traditional medical specialty barriers.

HOSPITAL UNIT ORGANIZATION AND STAFF

At Rancho, each unit is functionally separate with a large number of professional people working together as a rehabilitation team. In this way the patient suffering from chronic neuromusculoskeletal disorders can be easily and properly cared for. The rehabilitation team is led by a *physician*, who is primarily responsible for the patient's medical care and who coordinates the other members of the team. The *nurse* works closely with the physician and has perhaps one of the closest contacts with the patient. In the rehabilitation setting, someone must be in charge of the patient in his hospital activities. The patient at Rancho needs to learn to take care of himself rather than have services performed on and for him as in an acute hospital; he needs to be taught, assisted, stimulated, and encouraged.

Following the period of hospitalization, it is very important to continue the care within a patient's home or whatever facility may be required. The *liaison nurse* should lead this coordinating effort.

The role of the *physical therapist* in a rehabilitation program is to help prevent and correct deformities. The patient's gait needs to be analyzed. Weakened muscles need to be tested, trained, and strengthened by the use of a variety of special techniques and in the skillful use of specialized equipment. In our setting, the *occupational therapist's* activities largely center around upper extremity function, and involve the teaching and training of patients in the activities of daily living and in vocational testing.

Orthotists and prothestists are vital members of the team. They have certainly made their mark in their work with amputees, but there is much need for further research training and clinical application of their knowledge to neuromuscular problems in the rehabilitation hospital or center.

The *social worker* is an integral part of the rehabilitation team, for the patients we are concerned with are tremendously socially disabled by chronic disorders, especially in relation to their ability to care for themselves, to their wage-earning capacity, to the family relationship, and to their isolation.

Clinical psychologists help the patient adjust to his disability from a psychological standpoint and also help other professional members of the team, including the physician, understand the severe psychological problems of patients with these chronic overwhelming disabilities.

Speech pathologists. The thought process of the brain-injured patient is confused, and he has difficulty pulling his ideas together in a logical manner. His thoughts may be understood with difficulty, or perhaps not at all, by staff members or his family. Because of this inability to communicate, the patient may withdraw from mental and communicative interaction with his environment. Thus, the speech pathologist who is primarily trained to treat these communication disorders can again aid both the staff and the patient.

Vocational preparation is the culmination of the total rehabilitation process. From the beginning to end, the combined efforts of the medical and allied health personnel are directed toward teaching the individual to make the best use of his physical, intellectual, and emotional resources, and thereby to assume a productively active and useful place in society.

Each member of the team is a highly skilled professional and certainly can function very well individually. As a team with a common goal, they have demonstrated their ability to give the patient with extremely difficult chronic disabilities and problems better hope for a rewarding and productive life.

APPLICATIONS

We will consider the hemiplegic patient to show how these different personnel can apply their specialized skills to the neurologically handicapped patient. Hemiplegia can be caused by many events, including cerebral palsy, cerebral vascular accidents, and congenital brain anomalies, or it may be the residue of trauma to the brain. In all these cases, the peripheral motor system is intact but the central control system has suffered damage. Once the condition has stabilized or is no longer rapidly changing, consideration of rehabilitation procedures can begin. The medical status needs to be evaluated by the physician. How the patient controls his muscles is important for function. Is it patterning? Or is there selective control of individual muscles? If a patient wishes to bend his knee, does the whole leg flex with it because of the brain damage? If so, and if he cannot selectively flex the knee joint alone, this would be patterning. Coupled with the brain damage, body image may be lost and a person can become psychologically impaired.

A patient suffering from a stroke on the right side exhibits a severe body image sensory defect on the affected side. Such a person may attempt to get out of a wheelchair with his arm in an arm sling and foot in a footrest, because he is just not aware of them.

In the spastic hemiplegic patient, the predominance of unopposed excessive muscle tone in certain groups of muscles over a period of time will cause contractures to form if they are untreated. Ranging and passive exercises by the physical therapist are necessary to prevent contractures and to maintain muscle tone in the weaker areas.

Spasticity can also be relieved by a nerve block or destruction (by cutting), by releasing the tendon, or by cutting the muscle. Structural contractures that are permanent must be relieved by progressive stretching or by cutting the contracted collagenous tissue mass or bound-down joint capsules.

In patients where walking is a problem because of ankle and knee instability, a double upright short-leg brace may be used. The Bicaal brace shown in Figure 8-1 has a bichannel adjustable ankle lock, allowing fine adjustments to be made anteriorly or posteriorly to alter the position of the foot for maximum support and balance.

In other patients, exercises, simple surgical releases, and bracing may not fully correct the imbalances that continue to interfere with function, and complicated surgical procedures must be planned. Before implementing procedures that would result in permanent changes, one must be sure that there is improvement in the patient's general condition and his body image.

With time, the stroke patient mentioned above becomes more aware of his right side after a period of a few months. Although his view of it is still not normal, because of this improved awareness, surgery can be planned for him. In the patient's leg, the tendons are pulling in a poor direction for walking. We can diagram this in the following manner: The foot is pulled into varus by a spastic unopposed anterior tibial tendon, which can be corrected by splitting the spastic tendon and putting it in a position that distributes the pull to make it more useful (Fig. 8-2).

Unfortunately, such operations are not always successful over a long period of time, and it may be necessary to combine surgery, physical therapy, and the continued use of a brace. Very careful periodic reassessments are needed, as the patient's general condition may change. The surgical technique of this type of operation is not difficult; however, we do not know the physiology of the in-situ muscle tendon unit and its intricate mechanical properties, and our means of measuring the forces that tendons exert are crude.

Another type of hemiplegia is the case in which selected muscle control to dorsiflex the foot is destroyed. A recent development, which has been used in selected candidates, is the peroneal nerve stimulator (Fig. 8-3), whose principal action is to stimulate the peroneal nerve to bring the foot up. This device was mentioned by Hambrecht in Chapter 7.

Figure 8-4 shows a patient with brain damage. The external peroneal nerve stimulator has been turned on, and the patient dorsiflexes her foot. With the aid of the stimulator she can walk without the brace that she normally wears. The stimulator must be shut off when the foot is on the ground, and this is controlled rather ingeniously by a cyclical turnoff switch in the heel, which operates each time the patient puts her heel on the ground during the gait cycle. Further development of this apparatus is being pursued in our Medical Engineering Laboratories to simplify the equipment and eliminate the problems that occur with external electrodes and stimulation. The objective is to implant the stimulator and use a radio signal, controlled at the heel, to turn the stimulus to the nerve on and off with each gait cycle.

We are perhaps less successful in the rehabilitation of the upper extremity in these hemiplegic patients. There are three main factors: (1) the sensory deficit in the hand; (2) very fine selective control is needed, whereas in the lower extremity function is cyclical and repetitive; and (3) any fine movement usually involves all three major nerves – median, ulnar, and radial.

The patient with a nonfunctional arm can get around by the use of a cane, which helps him keep his balance. The cane occupies the good hand, and he really cannot carry objects or do things while he is up and about. In such a patient, the structural contractures noted previously for the lower extremity develop quite quickly. Exercise and the use of a suspension sling (Fig. 8-5) help reduce this difficulty. We feel there is need to develop other devices and to apply them. Through cooperative efforts with our Communications, Power, and Control Engineering Lab, the "Rancho" electric arm, with its 7 degrees of freedom covering all movements, has been successfully developed and applied to a number of severely handicapped polio and spinal cord injured patients in whom no function would otherwise be possible. From this work, the teleoperator manipulators have been developed. In the hemiplegic patient, overcoming spasticity is the major problem, and we feel that we may be able to improve overall upper extremity function by exercising. If a mechanically programmed exerciser similar to these manipulators could be used to give a specific type and amount of exercise, then patterning detrimental to good function might be altered or useful patterns created. This would be especially helpful in saving time for our already overworked allied health personnel by providing specific inputs into the patient's rehabilitation program.

In summary, the multidisciplinary care of the neuromuscular disabled patient has been reviewed. Our common goal is independence for early mobility. At Rancho, the medical team has been fortunate in having been able to foster and incorporate research with our engineering groups in developing methods to supplement clinical treatment and management. Further advantages and benefits will come through increasing technological developments, and there is considerable opportunity in this area for many different disciplines with a common goal in neuromuscular rehabilitation.

DISCUSSION

Q. How does the patient activate those mechanical arms?

A. One method is that used in the Rancho arm, which is activated by a tongue switch. We are developing other methods that would use the cheek, or, in hemiplegic patients the good hand could be used.

Q. Implanted nerve stimulators would be fed by radio frequency signals. Is there any possibility of outside interference?

A. I think Dr. Reswick may go into this tomorrow (Chap. 14). This has been a development problem.

Q. What has been your experience with stereognosis in addition to this?

A. This has been a problem that occurs in a large number of patients who have suffered from stroke or cerebral palsy. We don't have enough experience at this present time to come up with solutions.

Q. Part of our experience has been that even if you can overcome the mechanical spastic restriction in the hemiplegic upper extremity, a significant percentage of patients – between 20 and 30 percent – actually have enough sensory loss that they can drop an object and be unaware of it unless they hear it drop. It is so massive that I believe one has to address oneself pretty carefully to the sensory component, and not depend purely on the motor part.

A. I agree with you fully. It is present not only in the upper extremity but in the lower extremity, so that the patient is not aware of where he puts his foot down. In the lower extremity, part of this has been solved by the use of a brace.

I thought it might be appropriate to mention in this environment that a manipulator was developed in a joint program with NASA.

Q. Have you used patterning machines that repeat effectively, where you can program special types of exercises with a computer?

A. This is in the stage of development. I think we have a promising machine. We are testing it.

Q. Have you used patterning machines on patients to find indicators of effectiveness?

A. Not yet.

Q. If you use the peroneal nerve stimulator over a long period of time, do you notice any adaptation – changes in the gait, especially when you turn it off?

A. The external peroneal stimulators can only be used over a short period of time because the patient has many other functions that must be accommodated in different ways. We have found that the patients are able to be more self-sufficient in this way.

Q. There are some reports that patients are able to lift their foot without the stimulator, after it has been used for a long period of time. Have you seen anything of this sort – actual physiological changes?

A. Not in most patients.

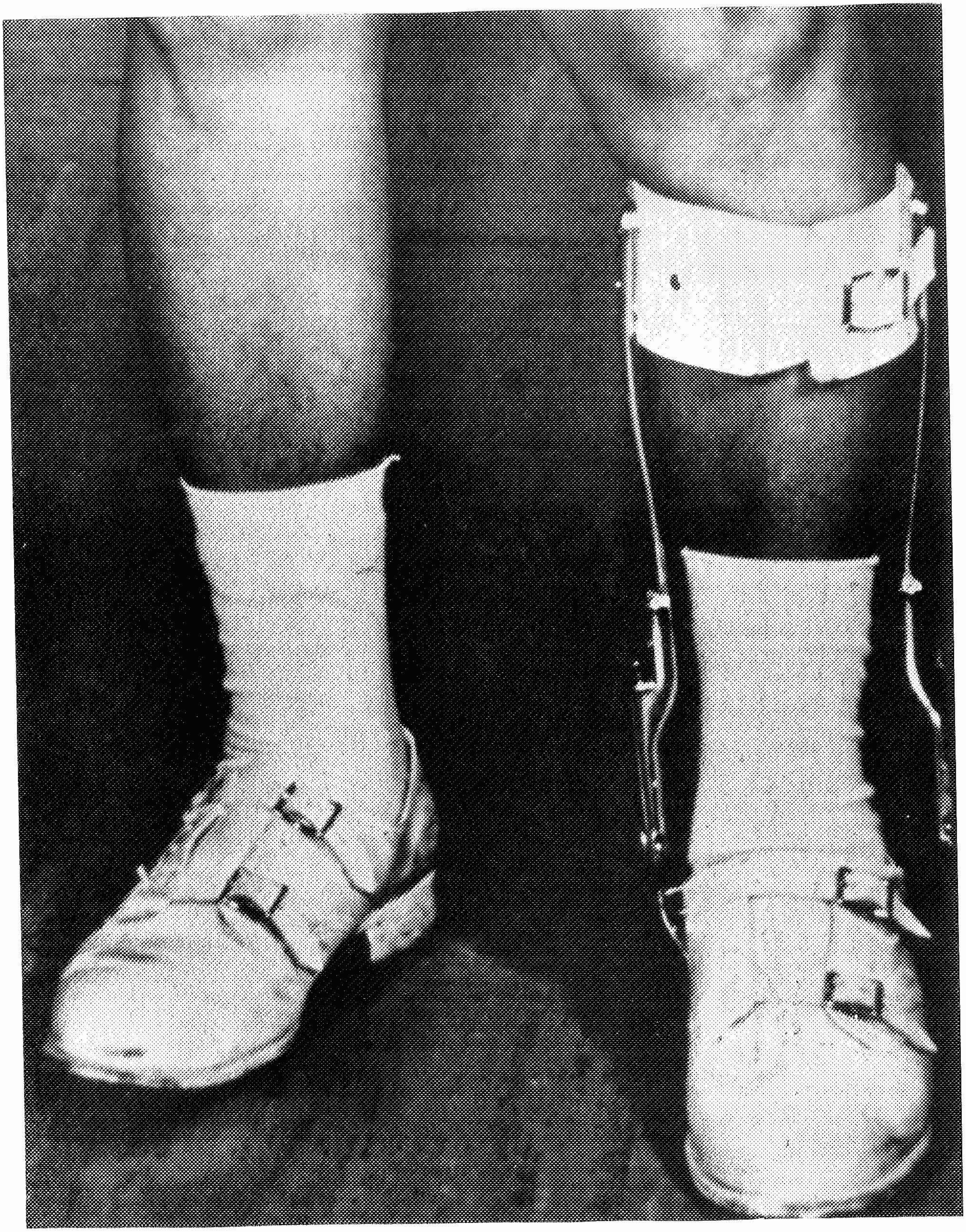

Fig. 8-1.– Double upright short-leg brace.

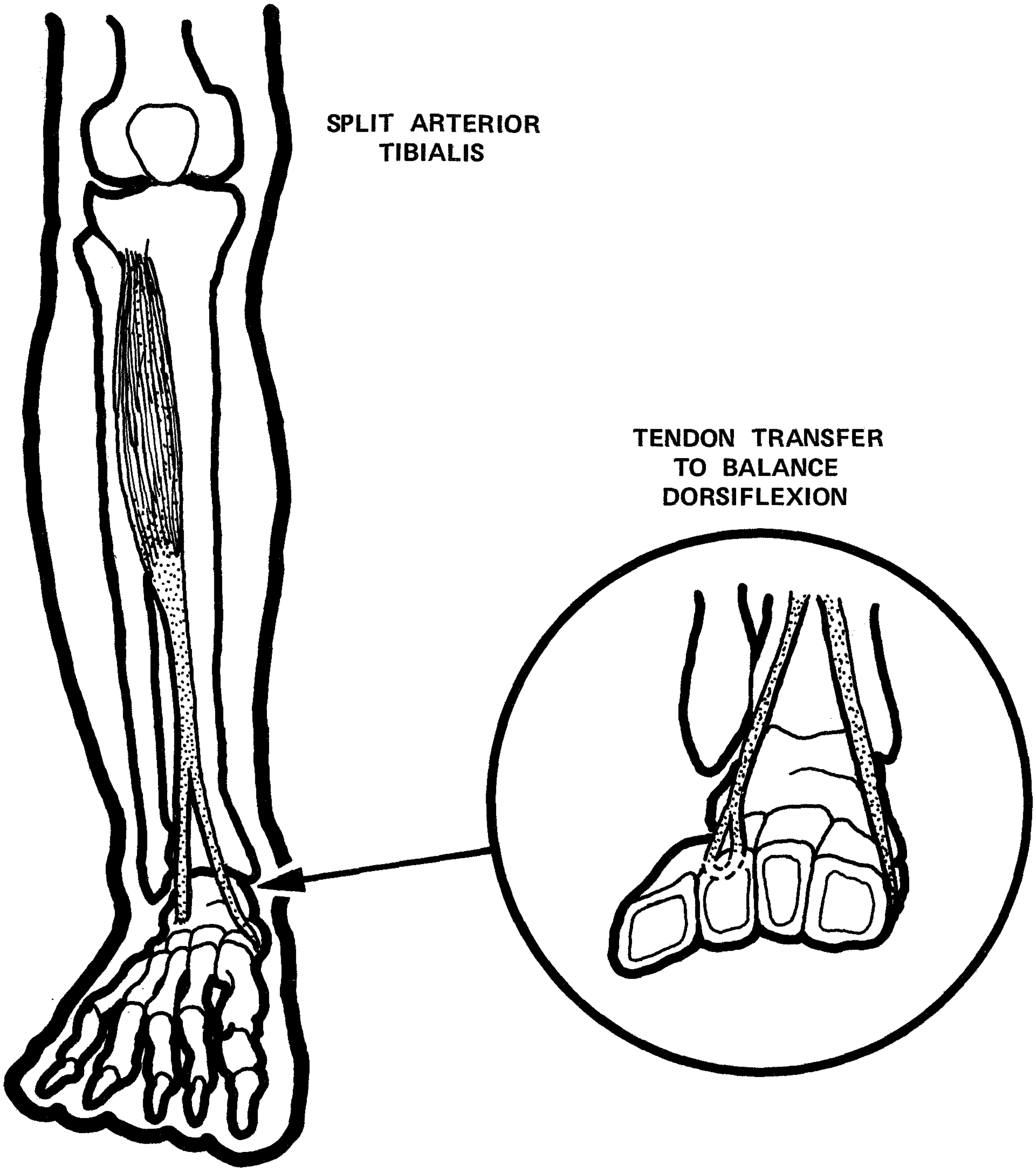

Fig. 8-2.– Distribution of tendon pull through surgery.

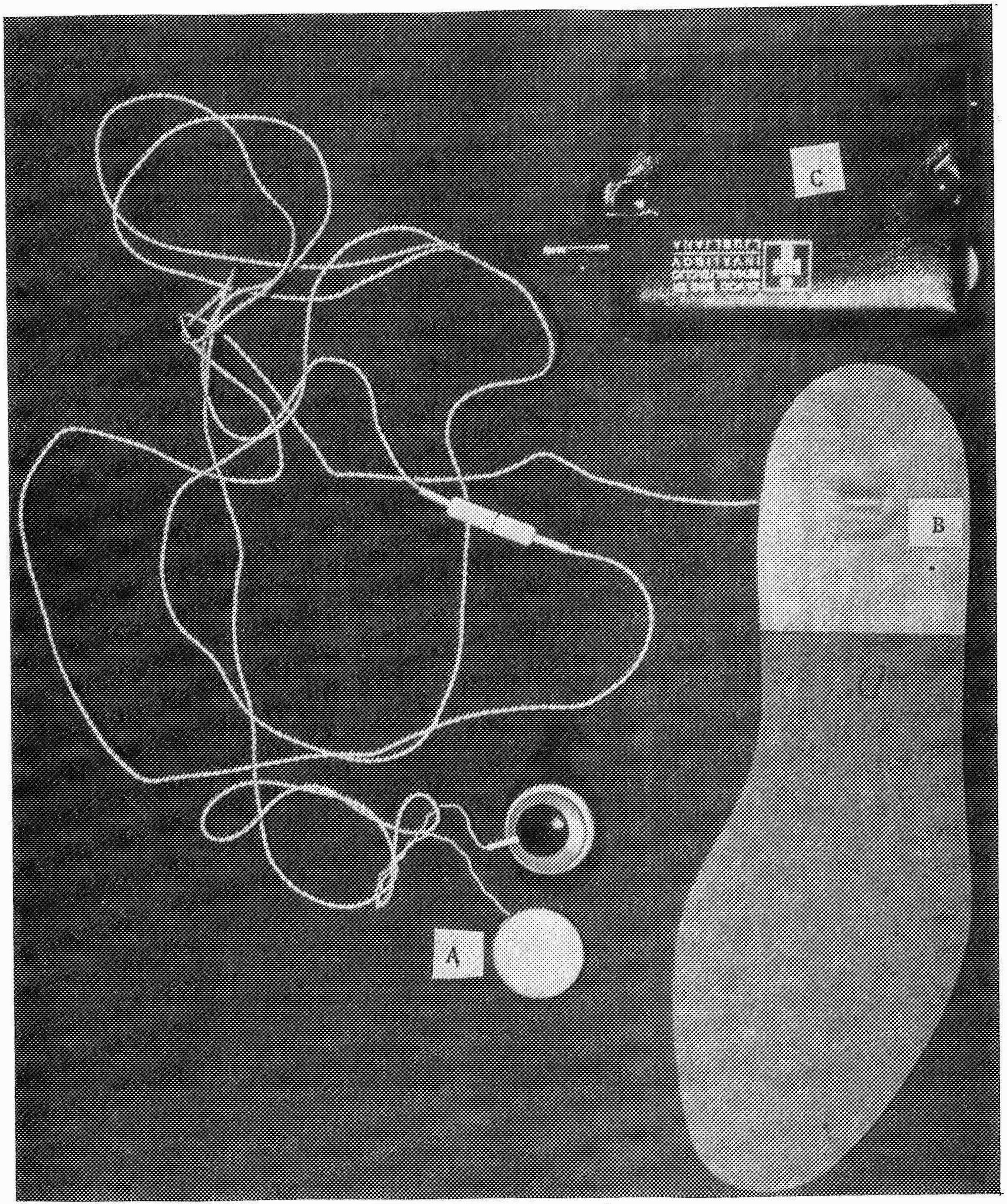

Fig. 8-3.– External peroneal nerve stimulator.

Fig. 8-4.– Application of the external peroneal nerve stimulator on patient with brain damage.

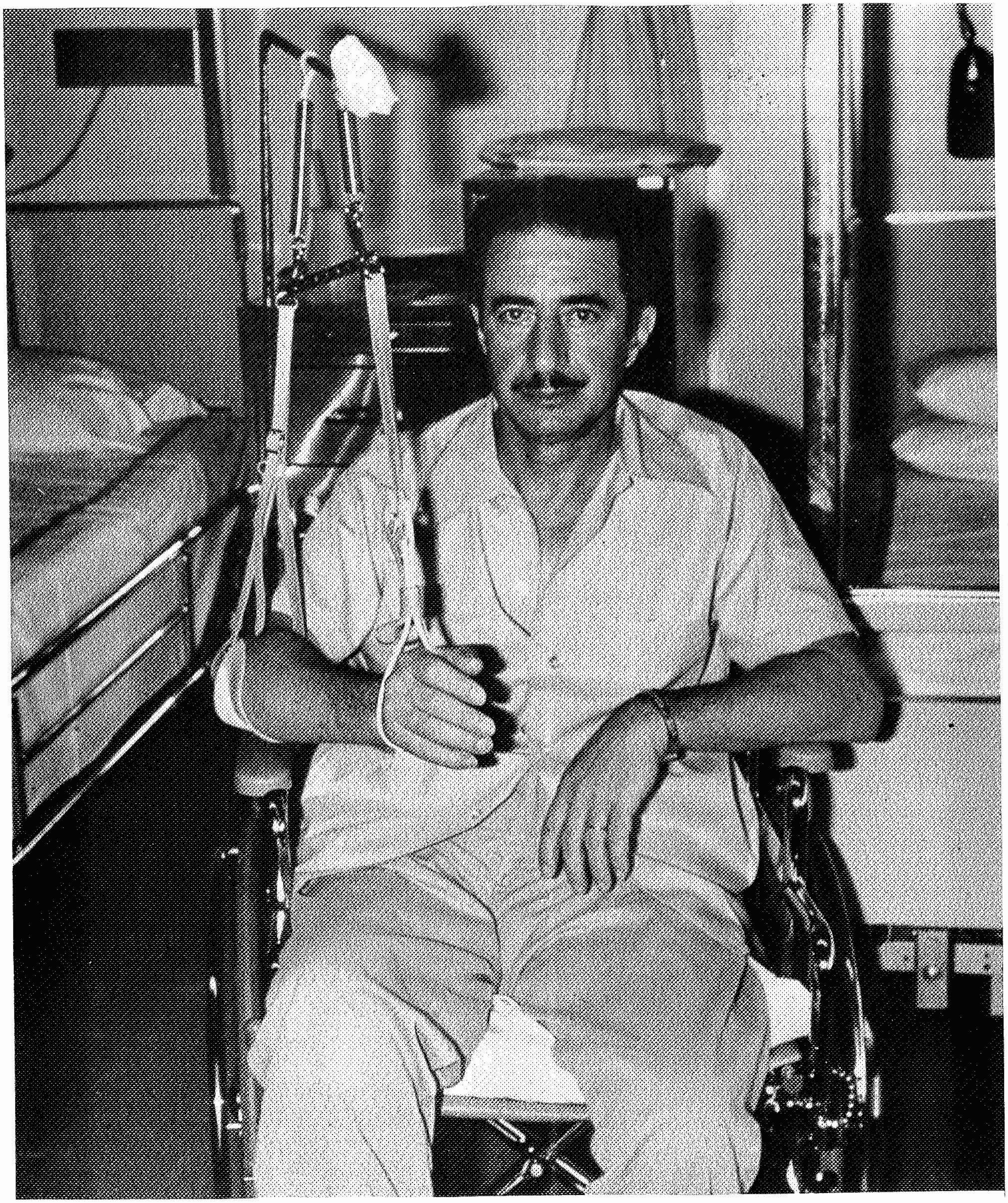

Fig. 8-5.– Suspension sling.

Chapter 9

THE USE OF OBJECTIVE MEASUREMENTS IN THE EVALUATION OF THERAPY PROGRAMS

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This chapter is concerned primarily with the importance of objective measurements as a means of assessing the efficacy of physical and occupational therapy programs applied to patients recovering from neurological diseases. We will consider three primary categories of neurologically injured patients: patients with hemiplegia, patients with spinal cord injuries, and the heterogeneous group of cerebral palsy patients. This selection omits a great many neurological diseases, but it does include a very large number of patients – somewhere between 2 and 3 million – in the United States. The cost of the rehabilitation of this very large group of patients is well over $100 million a year.

Now, having established that we are discussing a very large number of patients who are generating very large medical expenses for their rehabilitation management, we come face to face with a curious paradox. There is considerable difference of opinion as to whether physical and occupational therapy have any real beneficial effect on this group of patients. Is it possible that the conventional physical and occupational therapy dogmas and procedures represent a well-intentioned but essentially ineffective tradition that lacks any scientific base and any demonstrable efficacy but survives because of humanitarian response to the patient's obvious predicaments? This is a very hard question to ask, but a very real one.

We believe that one fundamental basis for this extraordinary situation has been the lack of objective measurements on neurologically disabled patients during the course of their illness. It is true that clinical neurology has access to a number of sophisticated tools for measuring electrical activity in muscles and in nerves, but these tools have certain limitations and for various reasons, they are not generally used in assessing the clinical course of patients with hemiplegia, cord injuries, and cerebral palsy. By contrast, the course of these patients is assessed by a variety of wholly or partially subjective evaluations of physicians, therapists, nurses, social workers, and, of course, the patients themselves. Bias and nonreproducibility of such evaluations are inevitable.

One of the simplest subjectively evaluated parameters used in assessing patients during recovery from central nervous system injury is the recording of deep tendon reflexes, which are usually graded from zero to four plus and correlate to some extent at least with the patient's level of spasticity. However, the procedures for eliciting these reflexes may vary considerably from one examiner to another. Posture, limb position, precise location of the tendon tap, and particularly the force of the stimulus are not controlled, and therefore not readily reproducible.

Furthermore, the characteristics of the reflex response are not objectively recorded, so that only the gross nature of the muscle contraction is evaluated visually by the examiner. Mechanical tendon-tapping devices have been designed, along with mechanical systems for recording the reflex response, but these have remained in the investigation stage.

Another frequently used and subjectively evaluated criterion is the level of the patient's *spasticity*, defined here as *increased reflex muscle contraction in response to passive muscle stretch*. The clinical significance of the phenomenon of spasticity is the subject of lively controversy. One widely held view is that spasticity is bad, and is associated with progressive disability in proportion to its severity. According to this view, spasticity in its advanced form is a devastating complication of neurologic injury. A contrasting view is that spasticity, except in its most severe form, is good and contributes positively to a measure of functional recovery in the neurologically damaged patient. Another view is that spasticity cannot be modified for better or for worse by physical or occupational therapy treatment programs. A contrasting opinion is that spasticity can and will be modified by physical and occupational therapy treatment programs; that the use of braces, slings, maximal effort exercises, and resistive exercises can make spasticity worse and is therefore bad; and that graded effort activities, emphasis on relaxation, and the use of various postural and synergistic responses can lessen spasticity and thereby maximize functional recovery.

A number of dedicated and respected physicians and physical therapists have been associated with treatment approaches directed at modifying spasticity. Karl and Berta Bobath, Signe Brunnstrom, Dr. Temple Faye, Dr. Herman Kabat, and Margaret Rood are some of the best known. Regrettably, none of these approaches has been convincingly demonstrated by objective measurements or valid experimental design to produce improved functional recovery that would not have occurred with simple common-sense hospital and home care. This is not to say that these treatment programs are *ineffective* – rather that scientifically acceptable proof of their efficacy has not been produced.

Scientific studies of all rehabilitation treatment techniques, including some of the mechanically monitored and performed exercises (Chap. 8) and even certain neurosurgical and orthopedic surgical procedures, must be studied scientifically in multiple large teaching centers, and the data gathered must include some reproducible objective measurements of the patient's status and performance during the course of his recovery period. The objective measurements must be rigorously standardized and characterized on normal subjects and, when possible, on untreated as well as treated patients. Above all, the measurements must be intelligently applied in the selection of patients with similar neuromuscular disabilities, so that truly comparable test and control groups can be appropriately defined. From the internist's viewpoint, a review of the rehabilitation literature reveals that the selection of patients as study subjects is too vague; they represent general diagnostic categories, but the specifics of their neurological disabilities are so poorly defined that it is very difficult to believe that test and control groups are sufficiently comparable to yield definitive results.

As an example, consider the measurement of spasticity. Generally, spasticity is evaluated subjectively. The examiner holds one limb segment in a fixed position and moves the attached segment passively, noting the muscular resistance that he encounters. It is impossible for the examiner to standardize the speed, the force, or the arc of the movement, or to record and quantify the resistance encountered.

Howard Bomze of the Biomedical Engineering Research Unit at the Irene Walter Johnson Institute of Rehabilitation in St. Louis has designed some equipment to provide objective measurements of spasticity. These measurements provide a basis for evaluating the physical and occupational therapy approaches to spasticity used in our institution and elsewhere in the country to determine the extent to which they are valid and useful. Bomze's equipment assures reproducible test conditions for passive movement, and provides permanent records of the muscular resistance provoked by that movement. In this discussion, we will be concerned primarily with test conditions for movements about the elbow joint.

Figure 9-1 shows a specially designed bench on which the subject is positioned for measurement. Positioning is extremely important to promote reproducible results, since reflex muscle resistance may be influenced by limb and axial alignment. The bench is designed for measurement with a patient sitting and is adjustable for various thigh lengths, with support provided by a broad seat belt and a shoulder harness.

Figure 9-2 shows the electromechanical system for producing the passive movement. The drive mechanism is an electric motor with the velocity servo-control. Mechanical stops and an adjustable upper torque limit ensure the subject's safety. The motor output is transmitted to the test subject by two mechanical arms, the stabilizing arm and the rotating movable arm. The forearm is secured at the wrist by a white inflatable cuff in an aluminum ring. Two adjustable electronic stops control the range of motion, and strain gauges with a sensitivity greater than 0.1 pounds force measure forces exerted on the aluminium ring during flexion and extension of the joint. A potentiometer indicates the position of the rotating arm with respect to the stabilizing arm. Four channels of electromyograms can be recorded during the testing.

Figure 9-3 shows the inflatable wrist cuff used for holding the movable limb segment. In Figure 9-2, this cuff was shown rolled up within the aluminum ring. As is true for every feature of equipment of this kind, it is essential to minimize incidental sensory stimuli, which could introduce artifacts into the muscle response. To ensure a firm circumferential attachment, previous workers have employed wrist casts made either of plaster or of polyurethane foam. This procedure requires a separate cast for each subject and for each limb to be tested. Furthermore, the cast becomes unusable if there is any local swelling or shrinking, and a new cast must be prepared. The inflatable cuff comprises six separate air chambers, which may be inflated to any desired pressure. Because the cuff is multicompartmental, there is negligible air displacement during the movement. The uniform circumferential pressure minimizes local stimuli over individual tendons or joint components, and the single cuff may be used at standardized pressures for all subjects and all limbs at any time.

During the measurement, the forearm is moved by the electromechanical system through a precisely defined cycle at selected speeds. A cycle is defined as motion from one position to a second position and then back to the original position – for example, from flexion to extension and back to flexion. During a movement cycle, a recording instrument plots force versus position and displays the data in the form of a hysteresis loop, as shown in Figure 9-4. The top curve represents the theoretical results expected for a 180° movement test cycle, if both mechanical arms are vertical at the beginning and at the end of the cycle and there is no muscular resistance during the cycle. Because of gravity effects, the tracing curves vary relative to the position of the rotating limb segment. The two traces of the loop are superimposed and form a solid line, since the effect of gravity is essentially the same in both phases of the movement cycle. When muscular resistance is encountered, an area is created between the two traces. This area is equivalent to the excess amount of work required to move the forearm through the cycle. The size and distribution of this area provide a quantitative expression of the amount of resistance to passive movement.

Clinical testing of patients and normal subjects has revealed four basic hysteresis loop patterns. The pattern shown for a normal subject moved through a 90° part of the total cycle most closely resembles a theoretical pattern, since the two traces are essentially superimposed and there is a negligible area within the loop. In the typical flexor pattern, resistance is encountered during the movement from flexion to extension, producing a convex upward deflection of the upper trace in the left half of the loop.

By contrast, muscle resistance is encountered during the movement from extension to flexion, producing an extensor pattern with a concave downward deflection of the lower trace in the right half of the loop. In some instances, resistance is encountered in both directions of movement and the mixed flexor-extensor pattern is obtained. It is clear that consecutive measurements of hysteresis loops under standardized test conditions could yield valuable objective data on the development and severity of spasticity during a patient's recovery from an acute neurological injury. It must be emphasized, however, that the range of technical and biological variation that may be expected must be determined before assuming that single isolated measurements represent a valid indicator of the general status of spasticity. Accordingly, we have made measurements under strictly standardized test conditions on ten consecutive days on normal subjects and on patients with chronic hemiplegia.

The results on two hemiplegic patients are shown in Figure 9-5. The hysteresis loops on the right show relatively little variation as compared to the marked variation on the left, where we see a nearly normal pattern on days 2 and 8, a markedly abnormal pattern on day 4, for example, and intermediate patterns on other days. Actually, under closer examination, the loops on the right exhibit variable features. For example, the diminished total areas on days 4 and 6 compared to other days are readily apparent. Note also the earlier onset of the flexor spasticity on day 8 as compared to that occurring on day 4. These variations among single measurements on consecutive days do not invalidate the measurement procedure. They are shown simply to illustrate the necessity of first characterizing the performance of any new evaluative tool before hastening too quickly to its application in following patients. As you would expect we have found that variation from day to day can be minimized if 6 to 10 cycles are recorded during a measurement session on any given day and the results averaged. Furthermore, optimum conditions for performing the multiple repetition so as to minimize variation within them are currently under study – for example, the optimum range of movement, the optimum speeds of movement, and the optimum time interval between repetitive movements.

We noted that averaging multiple cycles will reduce variation and thereby increase the validity of measurements on a given day. A number of interesting phenomena have been observed in our examination of the optimum conditions for reproducible repetitive cycles. In Figure 9-6, the hysteresis loops for six movement cycles are superimposed for a patient with a stroke in the chronic phase. The patient was resting and relaxed for at least 10 minutes prior to the repetitive movements recorded on the left; note the high reproducibility of the tracings in five of the six measurements. The patient then was asked to make five 3-second strong isometric flexor and extensor contractions and then relax, immediately prior to the repetitive measurements recorded on the right; note the marked increase in total area on the initial measurement cycle (the outside cycle) and the considerable variability in other of the cycles during this six-cycle measurement.

Figure 9-7 shows hysteresis loop patterns for movements about the knee joint and illustrates an interesting difference between a stroke patient on the right and a spinal cord injury patient on the left. For each patient, the upper panel shows superimposed hysteresis loops for six movement cycles where the time interval between cycles was 30 seconds. Good reproducibility is noted, I think, for each of these patients. On the lower panels, the time interval between each cycle was shortened to less than half a second. Good reproducibility is again observed for the hemiplegic subject on the right, but that marked variability with a tendency for progressive enlargement of the loop with each succeeding cycle is seen for the cord injury patient on the left. This difference in the response of hemiplegic and paraplegic patients in relation to the time interval between repetitive movements has been a consistent finding in the five paraplegics and hemiplegics examined to date.

The phenomena in the last two figures are simply examples of test conditions that can influence variability and illustrate the necessity for detailed characterization of test conditions before general application to patients with a variety of neurological disorders. All the measurements illustrated thus far have been for passive movements at a constant velocity. However, a great variety of programmed inputs can be utilized, certain of which may prove particularly useful in selected neurologic disorders. We are just completing a hydraulic drive system, which will be substituted for the electric drive system used up to now. The hydraulic system lends itself much more readily to more versatile control inputs and gives us greater precision control.

Figure 9-8 illustrates some of the possible input functions. These may be either constant, or sinusoidal velocity, which more nearly approximates normal movement patterns. A signal source has been built that has the options of single or multiple cycles, with or without variable delays at different points in the cycles for both waveforms. A short duration, low amplitude wave impulse may also be generated. All these movement functions will require careful study both in normal subjects and in patients. The hydraulic system will also lend itself to studies of active movements against controlled resistances. Recordings will be made of position, velocity, and acceleration of the patient's limb during the active movements.

Examples of controlled resistances are shown in Figure 9-9. The resistance may be kept constant, it may be varied throughout the range of the movement, or it may stimulate spring resistance, viscous resistance, or inertial resistance depending on the feedback utilized for its control. Such objective measurements on active movements will also require detailed characterization in normal subjects and in patients, and they should add valuable new dimensions to the evaluative procedures available for the study of recovery from neurological injury and the effective treatment thereof.

Evaluations of neurological patients should not be confined to objective measurements alone. The clinical value of objective measurements can be put in perspective only by correlating them with functional performance. Patients undergoing objective measurements in our laboratory are also subjected to a variety of functional tests; for example,

- Ambulation (timed)
- Stair climbing (timed)
- Wheelchair locomotion (timed)
- Transfers (able, unable, timed)
- Isometric strength (strain gauges, pounds)
- Rapidly alternating reciprocal joint movements (timed, range)
- Fine motor activities – buttoning, tying, positioning small objects (timed, accuracy)
- Gross motor activites – hand to mouth, to feet; knee extension, sitting; hip flexion, sitting (able, unable, movies)
- Activities of daily living, ADL (rating, scale)

Again, the test conditions should be standardized as rigorously as possible and the means for grading the results made as quantitative as possible – for example, the time required to ambulate or drive a wheelchair a specified distance, the time required to climb standardized stairs, and the number and range of rapidly alternating movements that can be performed within a specified time. As you can see, many of these activities do not lend themselves to precise control or quantification. But they are important, nonetheless, and they must be assessed by the best means possible.

We do not want to suggest that objective measurements made by machines such as we have described or the functional tests such as those listed above are sufficient in the total evaluation of recovery from neurological injury. There is the more complex but vitally important level of what might be called the life style of the patient. What activities does he actually perform when outside of the treatment setting? How does he interact and perform in his domestic, social, and employment environments? These activities are far more difficult to define and quantify, but they cannot be ignored in the total assessment of any treatment program. The complexity of their assessment should not paralyze us into inaction.

The equipment under development at our laboratory represents a very modest example of one kind of engineering approach to the evaluation of recovery from neurologic disease. It is by no means original in all aspects of its design. It is a very small drop in a large but presently almost empty bucket. Acceptance of the test procedures by patients has been excellent. The opportunity for developing other and better objective measurement techniques is almost limitless. Fifty years ago, the complexity of the task of assessing the efficacy of treatment procedures for neurologically disabled patients may justifiably have seemed overwhelming. But in the year of Apollo 17, there is little excuse for being overwhelmed. Cooperative studies at widely scattered medical centers throughout this country are a possibility. Standardized equipment and techniques for making objective measurements can and should be incorporated into any such multicenter effort. Computer analysis of complex data, whether they be in the form of historical details, pathologic findings, objective measurements, or functional assessments, is a formidable resource. If this conference can accelerate the application of modern technology to the assessment and management of patients with neurologic disease, it will have met a very urgently important need.

DISCUSSION

Q. It is interesting to see you go to hydraulics. I suspect some of the reason is because you want to get higher responses, measure acceleration versus force and so on, and the viscous drive. As you get into higher forces, I believe you find that in the general case at least, the use of the electric motors and gears result in such high effective inertia you can't get those responses. In other words, you can't beat, in general, the hydraulic drive mechanism in terms of torque or force compared to the weight and size ratios of the equipment. It is a practical way of going.

A. It is a great improvement.

Q. The other thing is in your measurements. There are two basic ways, I think, of measuring force. One is by simply measuring the hydraulic pressure generated at the hydraulic actuator; the more accurate way is external measurement with some kind of a force measure, an external strain gauge giving you better results.

A. That is what we are presently doing and plan to continue to do.

Q. Dr. Chaplin, in your objective evaluation device, do you see much point in going further than just measuring the hysteresis curves, and, for example, interpreting the hysteresis curves in terms of models of muscle, looking at numbers for different models of passive or active elasticity or viscosity?

A. We are getting very quickly out of my own range of special knowledge. But it seems to me that this is an obvious direction in which to go, and that the use of models is one of the many things opened up by making measurements of this kind. I think we have to go slowly at first, because this equipment turns out volumes of data, as you can well imagine. It has taken great self-control to do the studies on normal subjects. We have studied about 45 normal subjects, so far, trying to obtain a good spread of sex, age, and to some extent body configuration, muscle mass, and so on. And, of course, we need a huge body of this kind of data. There are certain things that have to be defined at a very simple level to start with. Perhaps we needn't wait to go on to modeling. But with our rather small operation, we are trying to do first things first. Certainly, modeling is a direction that should be very worthwhile. I should think the neurophysiologist would find it useful and interesting. Of course, my main concern is examining the effectiveness of physical and occupational therapy procedures. I do hope I haven't sounded as if I am antiphysical therapy or antioccupational therapy; I think they are great and they do terribly important things. I suspect they are doing some absolutely worthless things, as well, without realizing it, however, and I know that they are under severe criticism from very many highly critical and highly knowledgeable neurologists and neurophysiologists. I would like to see the position of PT and OT strengthened by evaluation of what they are doing and seeing whether they are really accomplishing what they think they are. But the other applications are very significant.

Q. In the recordings of forearm movement, (Fig. 9-4), what sort of speed did you use?

A. Most of them have been done at between 60° and 150° per second. Now, these are quite slow movements. We have done them at even lower speeds. We can go higher with the electrical drive system, but we get into more and more artifacts at the high speeds. By contrast, with the hydraulic system, our problem is going to be to keep the speed within a safe limit. We have put a goniometer on a patient and measured the speed at which the therapist does the usual subjective measurements and find, I think, that they get up to pretty near 300° per second in the ordinary clinical test situation. We certainly propose to look at higher speeds; we have observed that all these phenomena get bigger and bigger as the speeds go up. Of course, normal subjects show some increase at high speeds, but the increase shown in patients is very great. And there are all sorts of potentiating activities besides isometric contractions that can be done. Consider, for example, the patient whose right arm is hemiplegic and whose right arm is being tested; if he holds a 10-pound weight in his left hand during the test, there is a threefold increase in many instances in the size of the hysteresis loop in the measured arm. There are almost an infinite variety of test conditions that might turn out to be quite useful.

Q. I think this is a very good start, and I welcome it. I think probably the hysteresis loop is important. I think there was a conference several years ago in Boston in which the hysteresis loop was agreed on as perhaps the best subjective test and obviously you have made progress in perfecting it. I think there may be some semantic difficulty and maybe the editor of this program did you an injustice. You are not talking about the recovery from neurological disease, but rather the recovery from the early stroke – in other words, the change in neurological function, which is really not what you are concerned with here in many ways. Maybe you are in most instances.

The other point is that I think most of us who use physical therapy have given up the idea that physical therapy modifies or reduces spasticity. I think we use our therapy as a functional approach. My approach, particularly in the hemiplegic (which is a large group), very often is to emphasize recovery and development of compensatory functions in the opposite limb, the development of trunk balance and so forth. In other words, we are not talking about the return of neurological function in a static disability, but the compensatory adjustments that go on in total body economy in neurological function. Now, I'm wondering if you agree with this distinction between the return of neurological function in the impaired parts and the increased total function predominantly in the unimpaired parts.

A. Well, that is a big question, isn't it? I certainly agree that people in rehabilitation and in medicine generally must be cautious not to accept credit for recovery that is going on anatomically at a cellular level in the area of the damage. I also think, though, that the recovery of a patient after, say, a stroke, is almost certainly a combination of the anatomical recovery at the site of the lesion and the effects of what they are doing. If they lie immobilized, their recovery is going to be very bad. If they are doing certain things, their recovery will be better. So I think it is a system of many factors that are not easily dissociated. We have to think very hard, for example, about the value of pushing activities with the other extremity because this may increase the spasticity in the affected extremity. Now, this may not necessarily be bad. Again I think that with some objective measurements, we may get some answers to these difficult questions. What drives me crazy is to talk to someone who says, "I don't think we should do that any more, because I am sure Mrs. Jones is tighter than she was last week." And I go and I check Mrs. Jones and I am not sure that she is tighter at the time when I test her. And then I ask him whether he is really sure, and he says, "Well, she was at 6:00 o'clock last night." And pretty soon, we are just fumbling around. Now, believe me, I also know that a test done at 10:00 A.M. with a nice piece of equipment does not necessarily tell you how spastic Mrs. Jones is at 6:00 P.M. So we have a very complex situation. But I think we have controversial problems, expensive treatment programs that take weeks and months to apply in some instances, often proposed by very sincere, competent, experienced people, and we are not in a position to defend or condemn them. The point of this kind of equipment is to try to get a little firmer ground to stand on.

Q. Dr. Chaplin, don't you think you need some clinical correlates to go along with some of the objective measures? The point is, I think we have to start with some biases, contrary to what many people think abour research. If you don't start with a bias with some scientific basis, you sort of work at open ends and you get deluged by information of which you cannot make sense. It seems to me that we should not leave the engineer out too far on his own, and should provide some clinical correlates in order for both of you to converge at some point.

A. Well, we certainly agree. Within the limitations of time here, I discussed at least some of the clinical correlates that would have to be included – any other systematic disease the patient may have, a lot of detail about their localized neurological injury, and so forth. I don't know what, in particular, you may have in mind.

Q. Well, I can assume that not all of these patients are the same, even before I look at the objective results.

A. Right.

Q. I think we know certain things about alterations in the reflex activity that occur with structural changes in muscle and the difference in contractural properties versus elastic properties. And I think when patients are examined clinically, you get notions about these even before you put them on instrumentation. It seems to me that if we approach the problem with some clinical grouping and test our assumptions by the objective evidence, then we come closer to knowing what the objective evidence imparts.

A. Amen.

Q. But I don't think engineering can be expected to substitute for the clinical training background and knowledge that the physician brings to the problems. It can only assist and help.

A. I agree, and it is actually a lot of fun. There are a few tears shed, but it is a lot of fun. And I think some of the physicians around our institute now are maybe not quite as relaxed about their clinical evaluations, because we have told them we are very anxious to know what they think and because we are making some measurements and want to see whether what we are finding seems to agree with what they think or not. And they are beginning to call on the phone and say, "Have you done the measurements today? What did they show?" And I will say, "What did your clinical examination show?" You are right, these things absolutely have to be done together. And I think an engineer working too much without this kind of contact is going to waste time.

Q. How old is the youngest patient you have tested?

A. Eleven years old. There are two problems: one is getting the cooperation of a very small child, which is obviously a little more difficult, and the other is simply the sizing of our equipment at the moment. As you can see, it is sized pretty much for adults. I think to get really good results on a child, we would want to scale down, which is very easily done mechanically. But we haven't tried to go really into the pediatric population very much, partly because we really need patient cooperation. We try to avoid patients with enough intellectual impairment or confusion that they can't really understand what is going on and cooperate in it.

Fig. 9-1.– Bench on which patient is positioned for spasticity measurements.

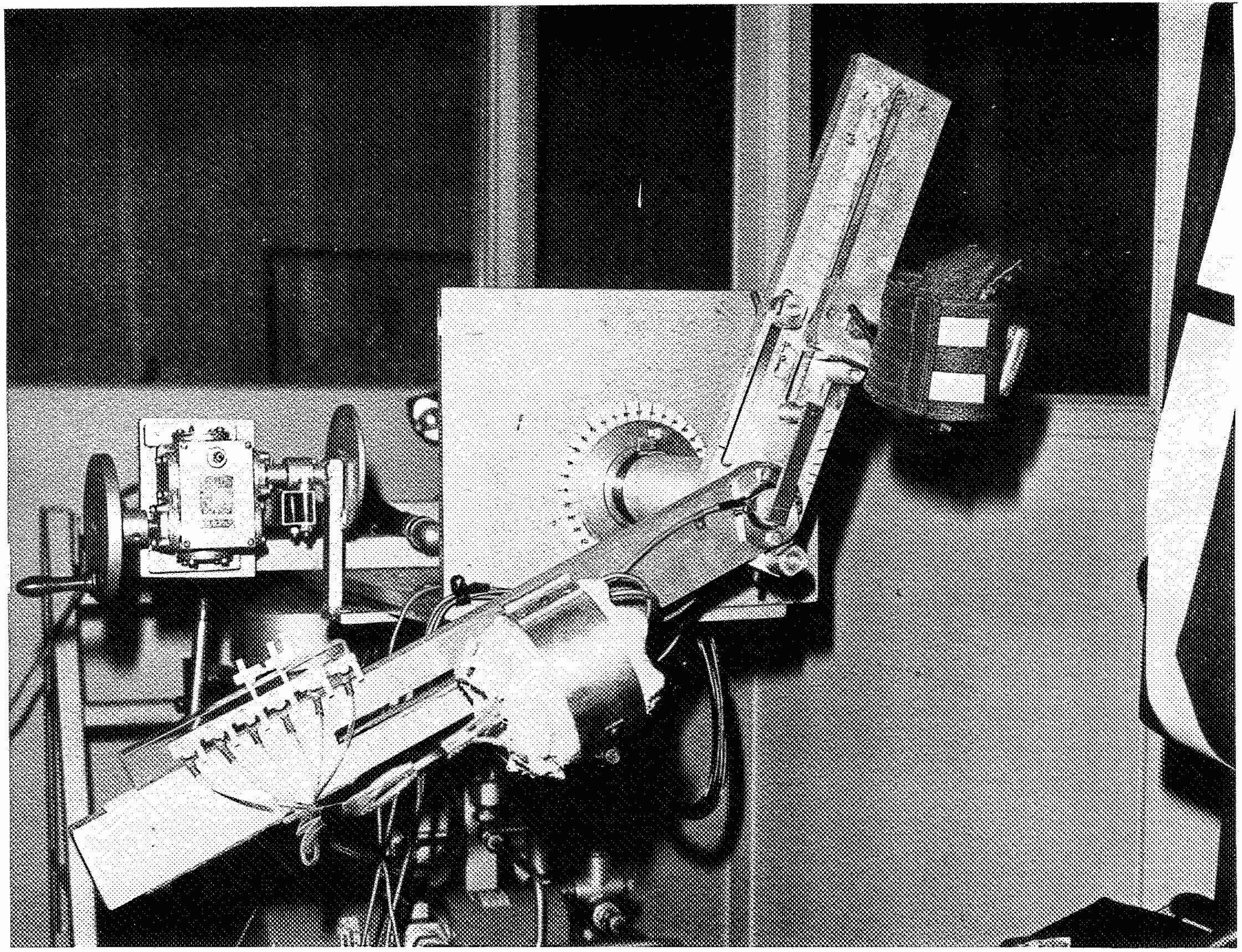

Fig. 9-2.– Electromechanical system for producing passive movement for spasticity measurements.

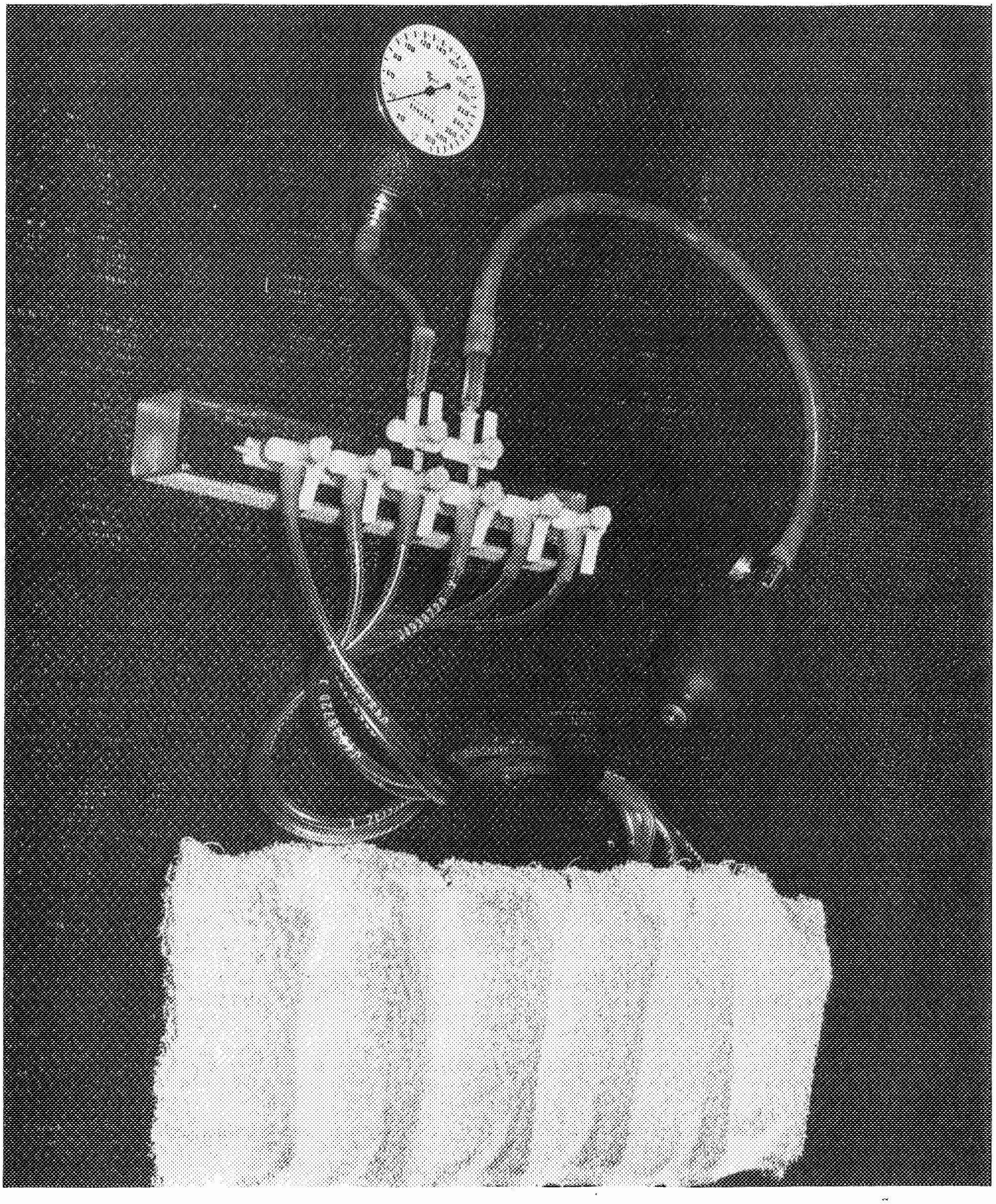

Fig. 9-3 .– Inflatable wrist cuff for holding movable limb segment to be tested.

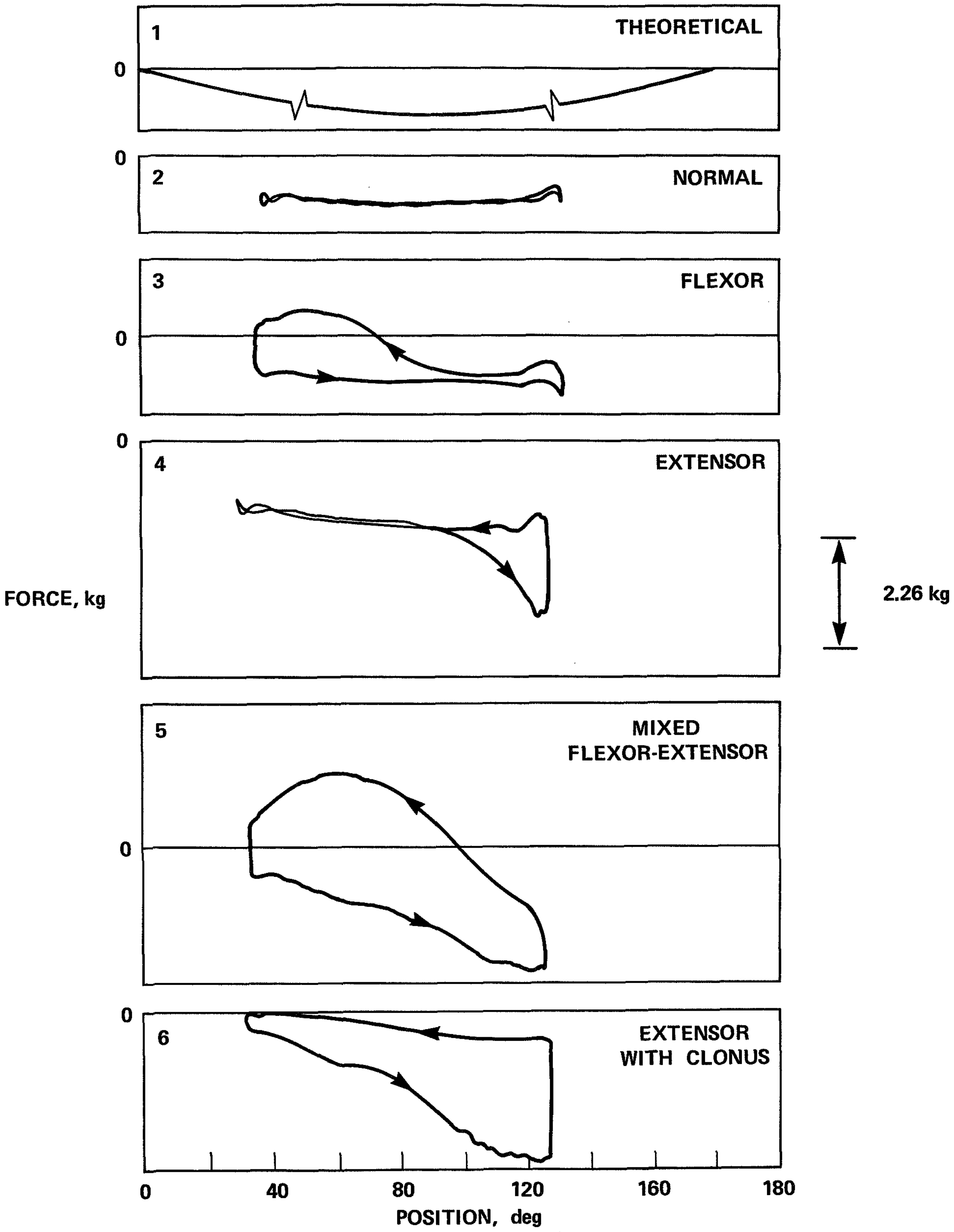

Fig. 9-4.– Recorded force versus position data in the measurement of spasticity.

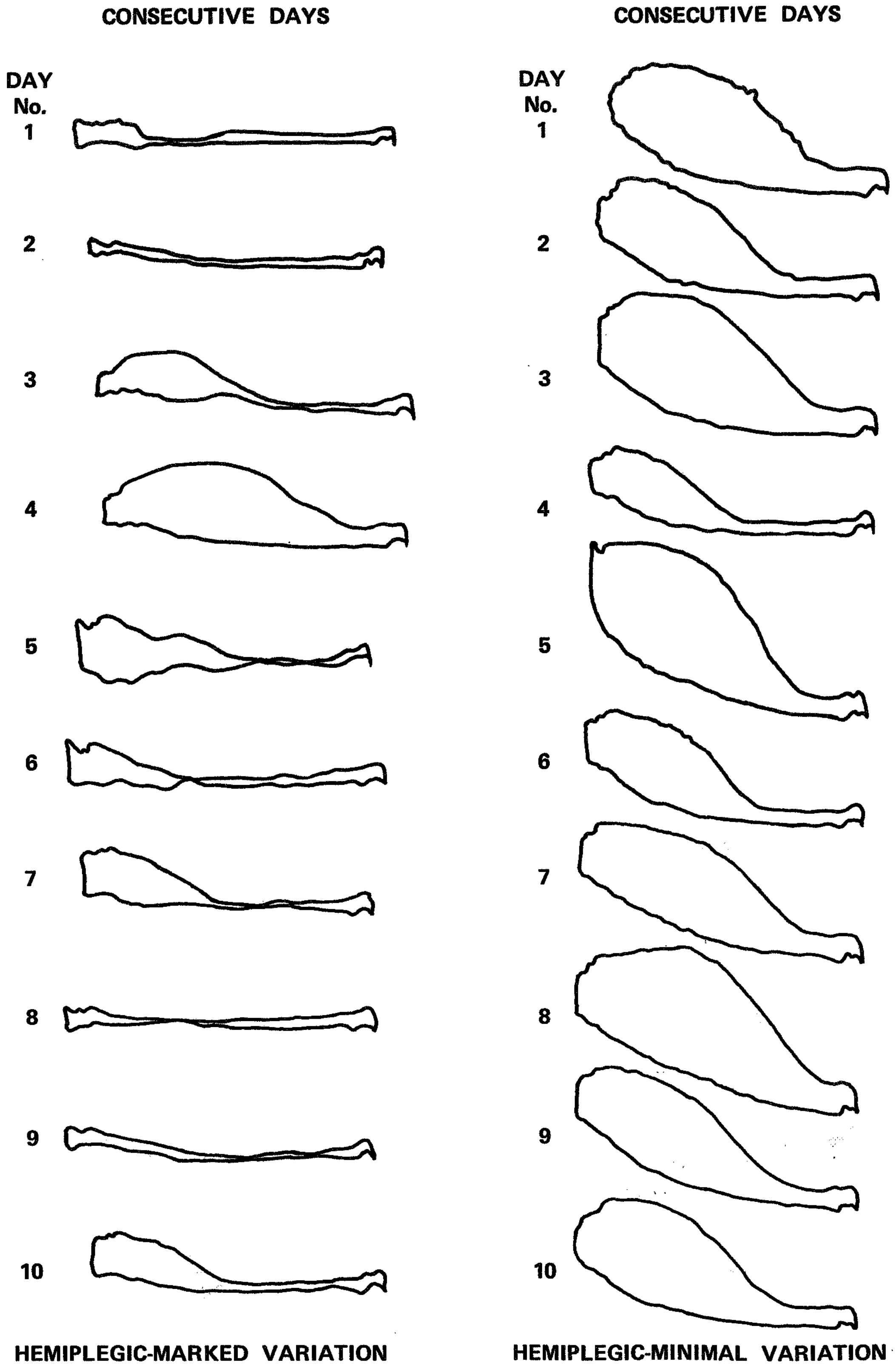

Fig. 9-5.– Spasticity measurement data for two hemiplegic patients.

(150°/sec)

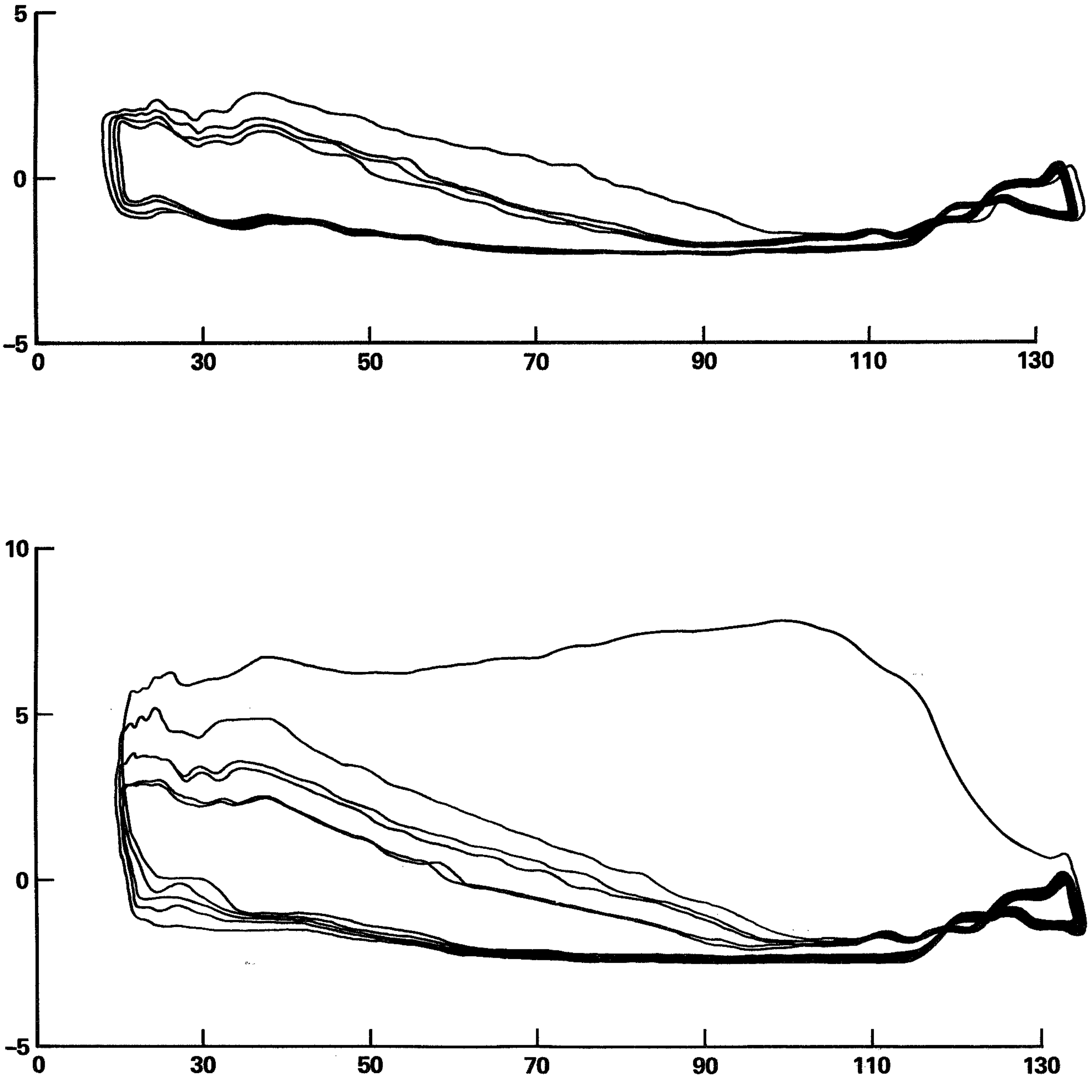

Fig. 9-6.— Hysteresis loops before and after isometric contractions.

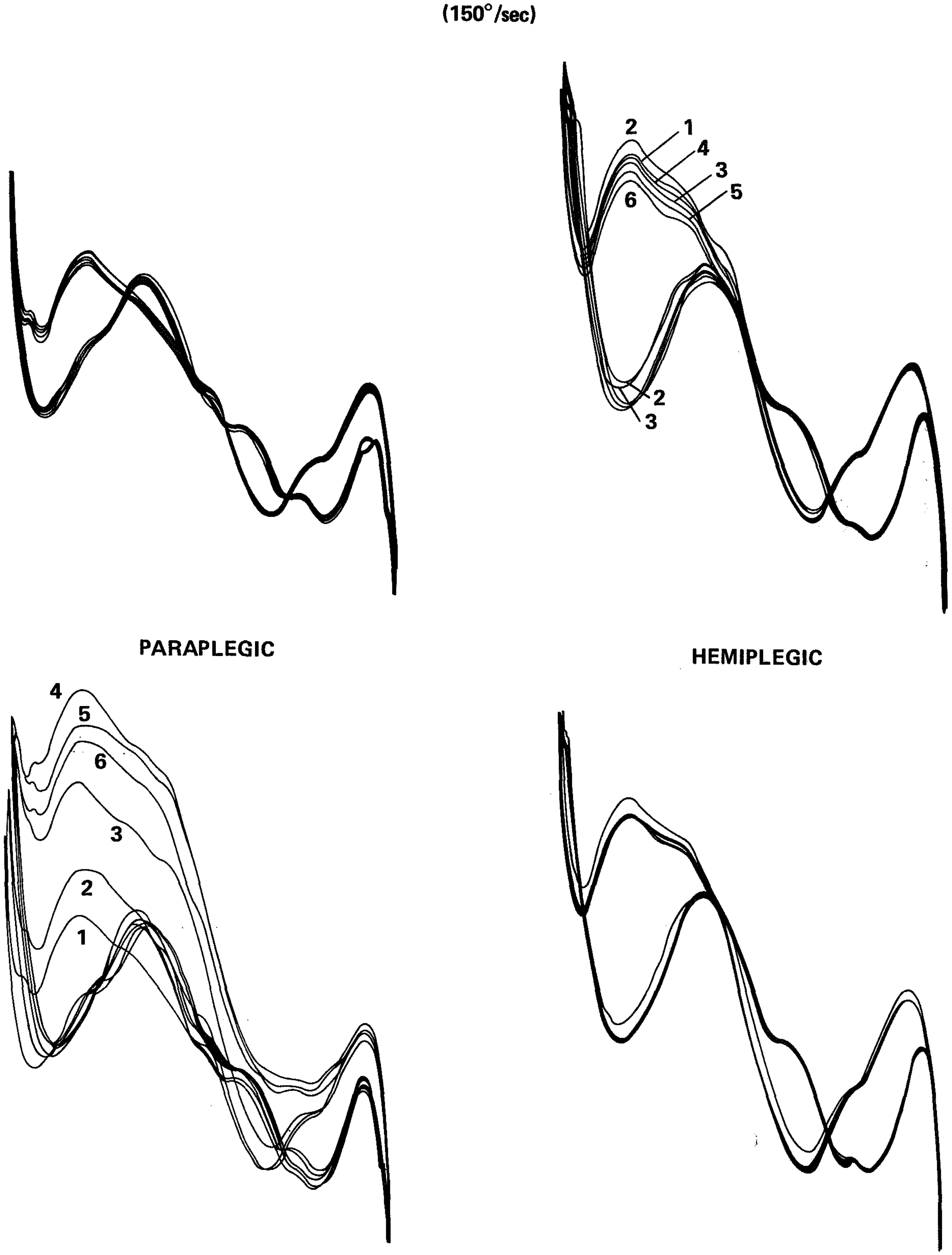

Fig. 9-7.– Comparison of hysteresis loop patterns for a spinal cord injury patient (paraplegic) and a stroke patient (hemiplegic).

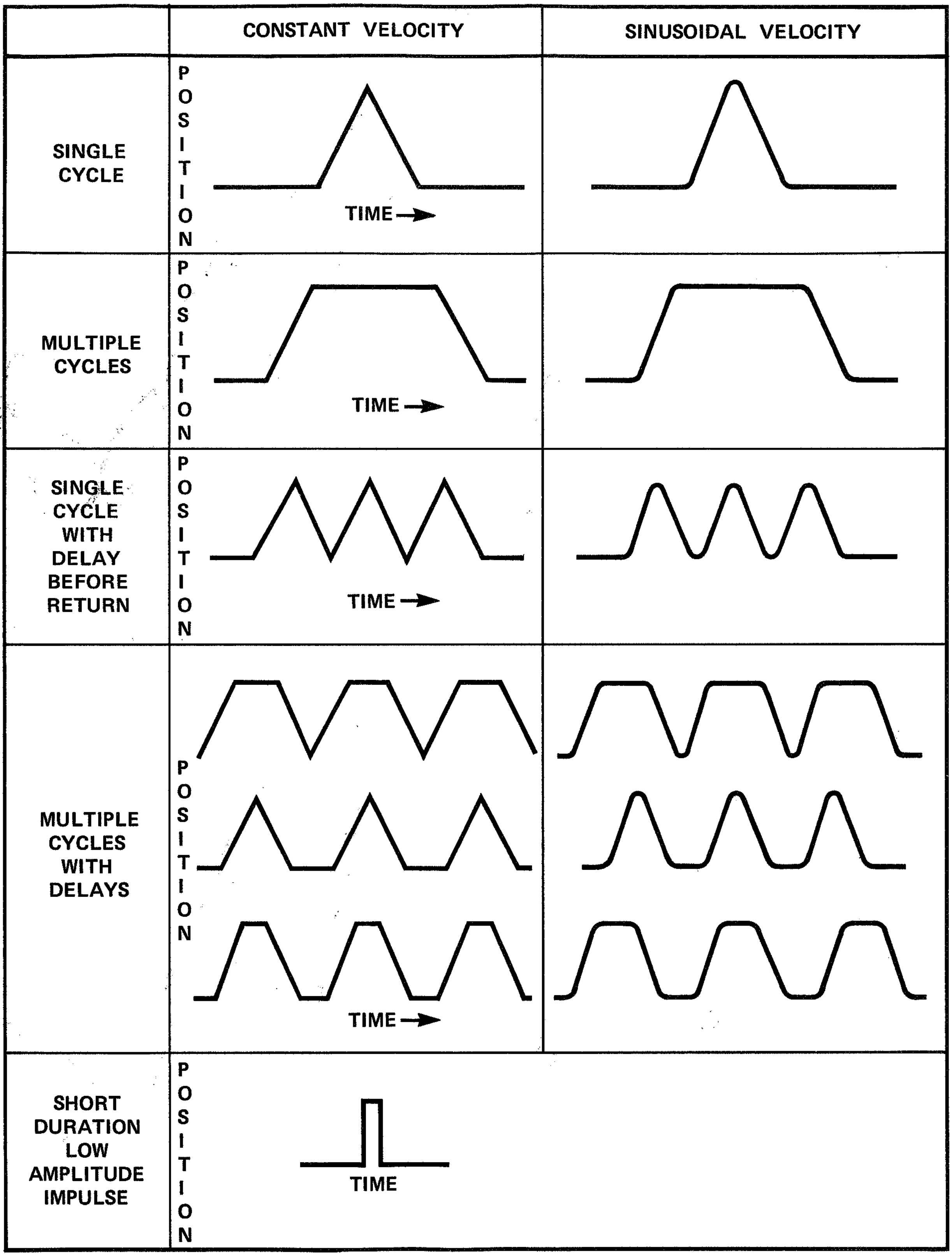

Fig. 9-8.— Passive movement functions.

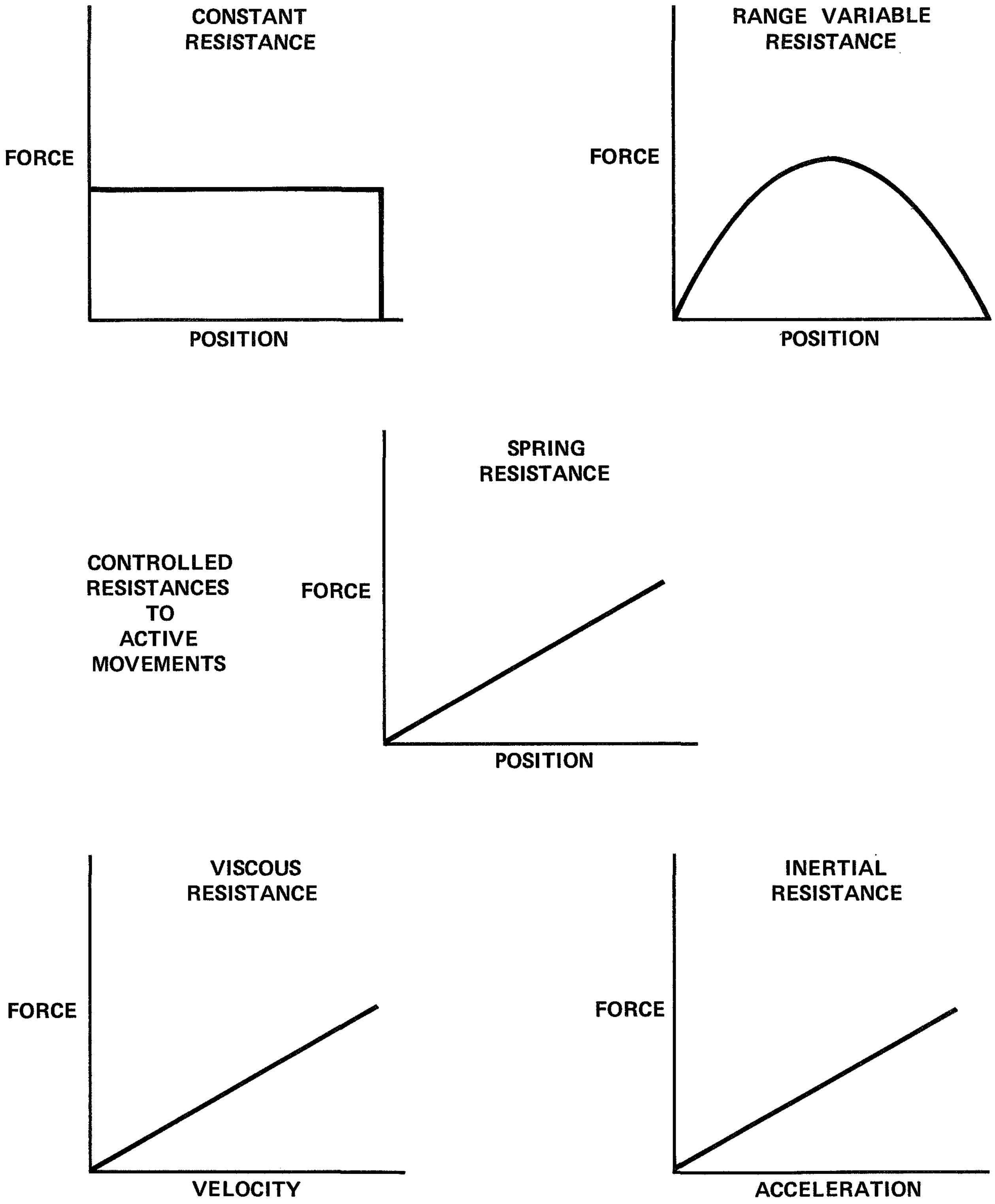

Fig. 9-9.– Controlled resistances to active movement.

Chapter 10

PROBLEMS AND PERSPECTIVES IN PARAPLEGIA

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Improved clinical treatment of the paraplegic, developed during World War II, has reduced the overall mortality rate from close to 100 percent to 30 percent. Despite major clinical improvements, mainly in treatment of the acute phase of paraplegia, and despite greater rehabilitation efforts, the spinal injured person is never rehabilitated in the sense that he reaches an optimum and stays there. He is always exposed to the constant threat of deterioration of his physiological, sociological, and psychological state.

THE HUMAN AND ECONOMIC IMPLICATIONS OF PARAPLEGIA

What is the dimension of the human problem? In 1965, there were 121,000 paraplegics and quadriplegics in the United States; in 1970, there were 47,000 cases due to direct injury to the spinal cord, and by 1990, this group will increase to 108,000.

Despite significant advances in medical care, the initial mortality rate among paraplegics during the acute phase of injury is 15 percent; the later mortality rate is 35 percent and is due mainly to renal disease. Suicide alone is responsible for 11 percent of the late deaths in paraplegics and occurs mainly among the younger ones. Thus, reduced renal disease and suicide rate would be a significant advance in the treatment of paraplegics. These and other factors in the mortality and morbidity rates of paraplegics are summarized in Table 10-1.

Table 10-1

MORTALITY AND MORBIDITY RATES AMONG PARAPLEGICS

Cause	Percent
Acute injury effects	15%
Renal failure	32
Renal plus amyloidosis	15
Renal plus hypertension	8
Pulmonary complications	7
Suicide	8
Neoplasia, bladder	6
Other	9

Following World War II the Veterans Administration organized special centers for both the acute and chronic phase of rehabilitation of the veteran paraplegic, and recently these centers have been updated through expansion of trained personnel plus supporting research projects relating to spinal injury (Chap. 4). The long-term care of civilian paraplegics, however, still lags way behind the Veterans Administration because of the lack of a coordinated national rehabilitation program. It would seem that NASA could supply invaluable expertise for the organization of such a program through its extraordinary ability to bring together such diverse groups as government, universities, and private industry.

As an indication of the magnitude of the economic problem, insurance companies must set aside a cash reserve of $250,000 to $500,000 for each case of complete spinal injury. It has been estimated that the initial cost per case is $20,000 to $40,000; and the total annual cost of spinal injury in the United States is $2 billion. A population of 3 to 5 million people is required for the support of one spinal injury center operating 50 to 100 beds.

ELECTRONIC NEUROPROSTHESES

Excellent clinical and basic research has been done over the past 25 years, and care of the paraplegic has been greatly improved through the efforts of many researchers and clinicians. Major medical and social problems remain, however.

Improved functioning of the paralyzed bladder through the application of electronic neuroprostheses is an interesting recent example of work in this field. The bladder is the guardian of the renal system, and when it fails, as it does in paraplegia, renal disease becomes the major factor in reduced life expectancy. The use of electrical stimulation to study the effect of the nervous system on bladder function was first explored in 1864, by Budge, a German physiologist who stimulated the exposed spinal cord of animals, producing bladder contractions, and by this means was able to trace, in a crude way, certain of the neural pathways within the cord that were responsible for the bladder function. The first attempt to trigger the bladder in a human by an electrical stimulus was carried out in 1940 by Dees, who used a device for transrectal electrical stimulation on himself and later in patients in an attempt to facilitate bladder emptying. Not a single medical journal would publish his results, because of the way-out nature of his work. Fortunately, Dees' manuscript was published some 15 years later, after he became a senior urologist in this country. In 1952, Bors stimulated the pudendal nerves of paraplegics for the same purpose. But the first major breakthrough was achieved in 1963 when Bradley and his group in Minneapolis implanted electrodes directly on the wall of the bladder in seven paraplegic patients. They used a radio frequency stimulation technique to directly activate the detrusor muscle of the bladder. Their method was not a complete success from the clinical point of view, because although the bladder wall would contract, the spread of the electrical current into the perineum resulted in pain and premature closure of the external sphincter with interferencing in voiding. Bradley and his co-workers have continued their research and have made some elaborate designs with electrodes for stimulating the bladder directly. Figure 10-1 shows how complicated an electroprosthesis can get. Taking the first hint from Budge's earlier work, we have approached the problem somewhat differently than Bradley and the others through direct stimulation of the spinal cord region. The neural control center for bladder contraction lies at the lower end of the sacral cord in a region called the *conus medullaris*. As shown in Figure 10-2, it is a complex region made up of both afferent and efferent neurons, and when the reflex is normally initiated, a common signal is sent out to the bladder from the S-1, S-2 level, via the sphincters, resulting in voiding of urine. This neural region often remains intact after a spinal cord injury, and we wondered whether or not this reflex center, even though isolated from the higher command centers in the brain by trauma, was still viable and capable of responding to crude electrical signals. Our observations both in animals and now in man have shown that this *micturation center*, as it is called by the physiologists, can be triggered by electrical pulses of a specific nature causing the bladder to contract on electrical command.

A special radio frequency electrode system was designed and built by Rodger Avery, an electrical engineer skilled in the design and construction of medical electronic devices. Figure 10-3 shows the little prosthesis, which is placed on the S-1 part of the conus through a laminectomy site. The implant is attached to an RF generator, which is a small passive transistorized receiver, buried subcutaneously, with an antenna placed above it on the skin.

Figure 10-4 is an artist's conception of the prosthesis and the conus medullaris exposed at surgery. Note the small platinum electrodes, about 2.5 mm long, which are inserted into the central gray portion of the cord. Stimulation across the region between the two electrodes causes electrical activation in the central area of the cord. This region was delineated by animal experimentation and is checked at the time of the surgical procedure.

Clinical observations have been made in four paralplegic patients using this spinal neuroprosthesis; three are emptying their bladders every few hours on electrical command from a small external RF generator, and are free of catheters or other drainage devices – which allows them psychological and physiological freedom.

The obvious purpose of this type of neuroprosthesis is to control the bladder, allow adequate emptying, and thereby reduce infection and later renal complications. This device has now been functioning well in three patients from six months to one year: of course, it is still in the experimental stage. Only two bouts of bladder infection have been experienced in these patients since the implantations, and these were associated with power failure of the batteries in the external RF stimulator, resulting in a weak signal that was not adequate to contract the bladder. When this deficiency was corrected with fresh batteries, complete voiding resumed and the infection cleared up.

The stimulation afforded by this device also activates the muscles of the paralyzed lower extremity, along with the automatic neurons in this area of the cord, resulting in penile erections in males, sweating, a rise in skin temperature, and probably increased blood flow to the paralyzed legs. The beneficial effects of these additional physiological responses of the paraplegic have not been fully determined since our studies have concentrated on the bladder.

What are the future possibilities for the use of similar neuroprosthesis to control nervous function? NASA's ability to develop highly sophisticated sensor devices for recording and transmitting pressure, motion, light, sound, and other information coupled with cooperative efforts between the electronic engineer and the physician suggest some new and exciting applications. If one can exert electronic control over the spinal cord to improve bladder function, would it not be possible to control certain aspects of sexual, hormonal, or metabolic functions? The loss of mobility with paralysis of the legs is a serious problem to the paraplegic. A few visionaries have suggested the possibility of electronic muscular control. Wendall Krieg, for example, a distinguished neuroanatomist at Northwestern University, writes:

> It ought to be possible to place electrodes over denervated muscles and by activating them in proper sequence and intensity, produce useful movement. In conditions where the motor nerves and muscles are normal but central organization and control is at fault, resulting in faulty muscle tonus, it may be possible, by placing retention electrodes at proper control points, to inhibit or exact tonus or activity.

Now, this is not a crackpot speaking but a distinguished scientist calling on each one of us not to lose our nerve over these difficult tasks, but to try to improve the lot of our fellow men. Certainly, the telemetry of sensor data, the miniaturization of electronic components, and the preprogrammed portable computers for complex command functions are waiting in the wings for direct applications in medical science.

It is not possible at this time to define all the problems. There are many, and each of us with his own special interests must seek out our colleagues in the physical sciences to form working partnerships. NASA could have its greatest impact in encouraging and furthering these partnerships.

CASE STUDIES

One patient studied is a teen-aged paraplegic, who was paralyzed three years before we saw him. He had a small contracted spastic bladder. He had multiple bladder infections. He did not develop a reflex neurogenic bladder. His sensory level is just about the midabdomen. He developed really no hyperactivity or spasticity in his legs, which many paraplegics do. He is a traumatic paraplegic with a complete lesion, both motor and sensory. Cystometrigrams are done numerous times on such patients to test the capacity and reflex activity of the bladder.

With the implant in the conus, we can exert some kind of control over the muscles of the lower extremities, although this is not to imply that we are going to make anybody walk. Stimulation of about 10 Hz elicits a response from the paralyzed leg as a result of feedback into the cord.

More stimulation results in increased goose bumps and the raising of hairs on the skin of the lower extremities – in fact, over the entire lower part of the body. This phenomenon is an autonomic response to the stimulation, and along with it there is a marked increase in the skin temperature and probably an increase in the blood flow (although we have not measured it yet) in the extremities.

It is not known what these physiological phenomena can do for the paraplegic, but they are interesting. We are activating a whole spectrum of neurologic functions.

The patient uses two controls – one for the frequency response and one for the voltage. (Interestingly enough, in the animal experiments a 15- to 30-Hz square wave of about 200 μsec duration was found to be the optimum stimulus.) In some of the males, we have had to partially interrupt the external sphincter, because this will intermittently contract and relax during the stimulation. This boy is able to go into the bathroom with his stimulator to empty his bladder. Sometimes there is a little bit of an erection as well. He can completely empty his bladder with the stimulus. It may taken from 15 to 30 seconds to a minute, depending on how full the bladder is. We usually use a schedule of stimulation about every four hours.

Another patient in the group is a female paraplegic. She has been paraplegic for four years, and yet her spinal cord was as responsive to the stimulator as the others. She can empty the bladder completely, with no residual urine. There is no interference from her external sphincter. It is possible, therefore, that female paraplegics may be best suited for this prosthesis.

It must be emphasized that this is an *experimental* device. We are still studying it, but we think it has some very interesting potential for the future and hopefully for the improvement of the paraplegic.

DISCUSSION

Q. Did you say you had these devices implanted for a year?

A. The longest one was a year, in the case of the young boy. We have six months to a year followup.

Q. Is there any change in the threshold of the stimulation?

A. No. This is interesting. We have measured the thresholds. We have the patient keep a record on the stimulus parameters they use. We have not noticed any change in the patient's thresholds or in thresholds in the animal experiments. One would expect some tissue reaction to the electrodes. Based on the threshold of stimulation, this appears to be minimal. We employ biphasic impulses, which alternately polarize and depolarize. Some people feel that this type of pulse reduces the amount of tissue reaction around the electrode. We have examined animal cords in the short-term experiments (weeks), and there are varying degrees of tissue response, with some hemorrhage.

Q. Does the muscular activity cease the moment this current is turned off?

A. No. It seems that once you start the electrical bombardment of the cord, then it will continue on for as long as 30 to 40 seconds afterwards, suggesting here the activation of reverberating circuits within the cord.

Q. Within a minute it is gone?

A. Yes, then it stops. But the motor responses go on beyond the stimulus-off signal.

Q. Are you planning to use this technique on other problems?

A. We have thought about it. We want to try to work this out. There are a lot of interesting applications. We now have an electrode design that can be actually put on the surface of the cord and does not require penetration – although penetration produces the best bladder response. This theoretically might be used, let's say, on a patient with a neurological disorder whose cord is intact (so that you wouldn't want to implant electrodes) but where some part of the reflexes are disturbed. It almost seems as if one is triggering the thing off on occasion, but you don't have to go and stimulate the whole period of time. Just the initial stimulus seems to trigger it off. Of course, a high percentage of multiple sclerosis patients die of bladder problems. There are other cases you can think of, such as women whose spinal cords are intact but who develop difficulties in bladder function and other neurologic disorders following hysterectomies.

Q. Following up this reflex idea, the effect you mentioned, with the afferent supplies still intact, did you find any correlation between the thresholds or duration of stimulation before micturation occurs and the degree of filling of the bladder?

A. We have done some of these studies in acute and in chronic animals, but not in humans. There is a relationship – I think the bladder reacts better if it is full – but that is about all I can tell you at this point. We haven't gone into such questions as whether it is worse if you stretch the bladder and so forth. In two patients with small contracted bladders, the bladder capacity increased, over the periods of stimulation, so that we go from a bladder of 100 cc in volume to a bladder now that is close to, say, 200-300 cc. We have also noticed this in the animals. What we've done in the animals is that we have stimulated them, measured their bladder volume, and then stopped stimulation for several weeks or months, with the result that the bladder size decreases. The bladder volume increases again with stimulation. We have some good data on animals, showing that you get a marked fluctuation in the bladder volume, depending on (we assume) keeping the contractility of the muscle up. We haven't looked at every aspect of the problem.

Q. What are long-term effects of the use of this prosthesis?

A. These people develop pressures up to as high as 90 to 100 mm Hg with electrical stimulation. Now, it only takes about 40 to 50 mm of working pressure for the normal physiologic emptying of the bladder, and the curves that show this look very similar in terms of the peaks of time intervals and how they stay up before they stop. But they are not exact.

Q. Was your drawing accurate as to the position of those electrodes in the region of the conus medullaris?

A. Yes, yes. That was what we tried to convey – the intermedial lateral cell column, which according to the anatomists is the parasympathetic center in the spinal cord. In animals, we did step-by-step, millimeter-by-millimeter stimulation through the center of the cord, with hundreds of passes of the electrode, measuring the bladder pressure each time stimulation was done. That central gray region of the cord in animals was the most sensitive, which is why we chose the area for the patient. The electrode is so constructed as to sit in the central part of the cord. I think one of our clinical failures in one patient was probably due to an anatomical variation with the result that the electrode was not in the proper position.

Q. Is there any difference in stimulating S-2, -3, and -4 bilaterally? Do you get more trouble with contraction?

A. Well, I haven't done that myself. From the reports of those who did, there is quite a difference. The effect is mainly on the bladder. When you look at this under cinefluoroscopy, you really see this very, very clearly.

Q. Have you had any problems with exourethral reflexes?

A. No. And that is another interesting thing. In direct stimulation of the bladder wall, as Bradley did, you often see reflux of urine into the ureters. We have not seen this during direct spinal cord stimulation. We believe the cord stimulation mimics the normal physiological response better than direct stimulation of the bladder wall.

Q. When you are putting the device in, do you stimulate the motor roots?

A. No. That is at the vertebral level, T-12, L-1. We surgically expose the conus medullaris, and then we have a very fine bipolar stimulating electrode, and start stimulating the dorsal surface of the conus. A catheter is placed in the patient's bladder prior to surgery. We begin by stimulating the dorsal surface of the cord, stepwise from the top down about every 2 mm and measure the resulting bladder pressure. At the point on the cord where the bladder pressure is the greatest, the depth electrodes are inserted into the cord and we restimulate. An X-ray of the spine shows that the implant site is at the S-1 cord level.

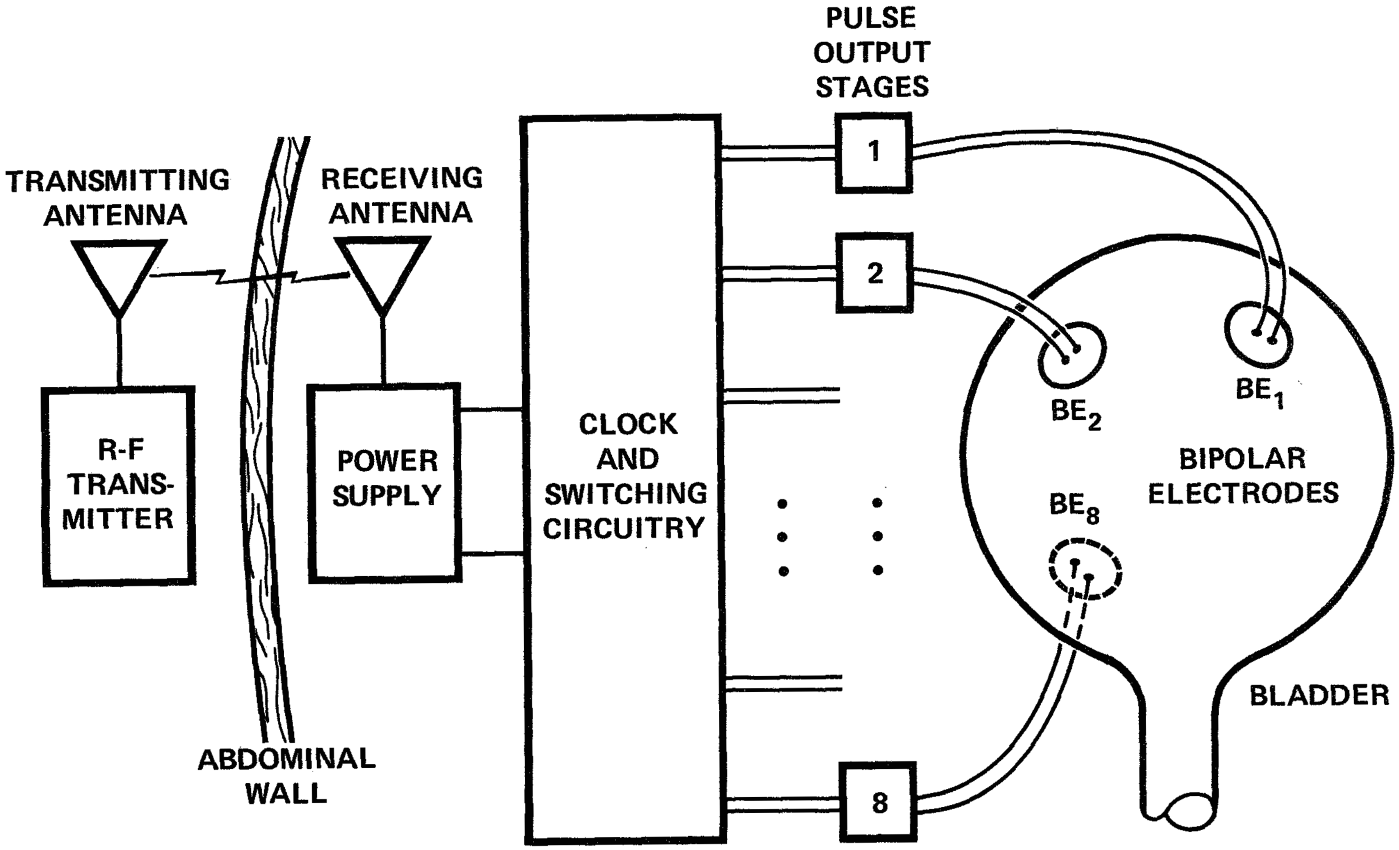

Fig. 10-1.– Electroprosthesis for bladder function.

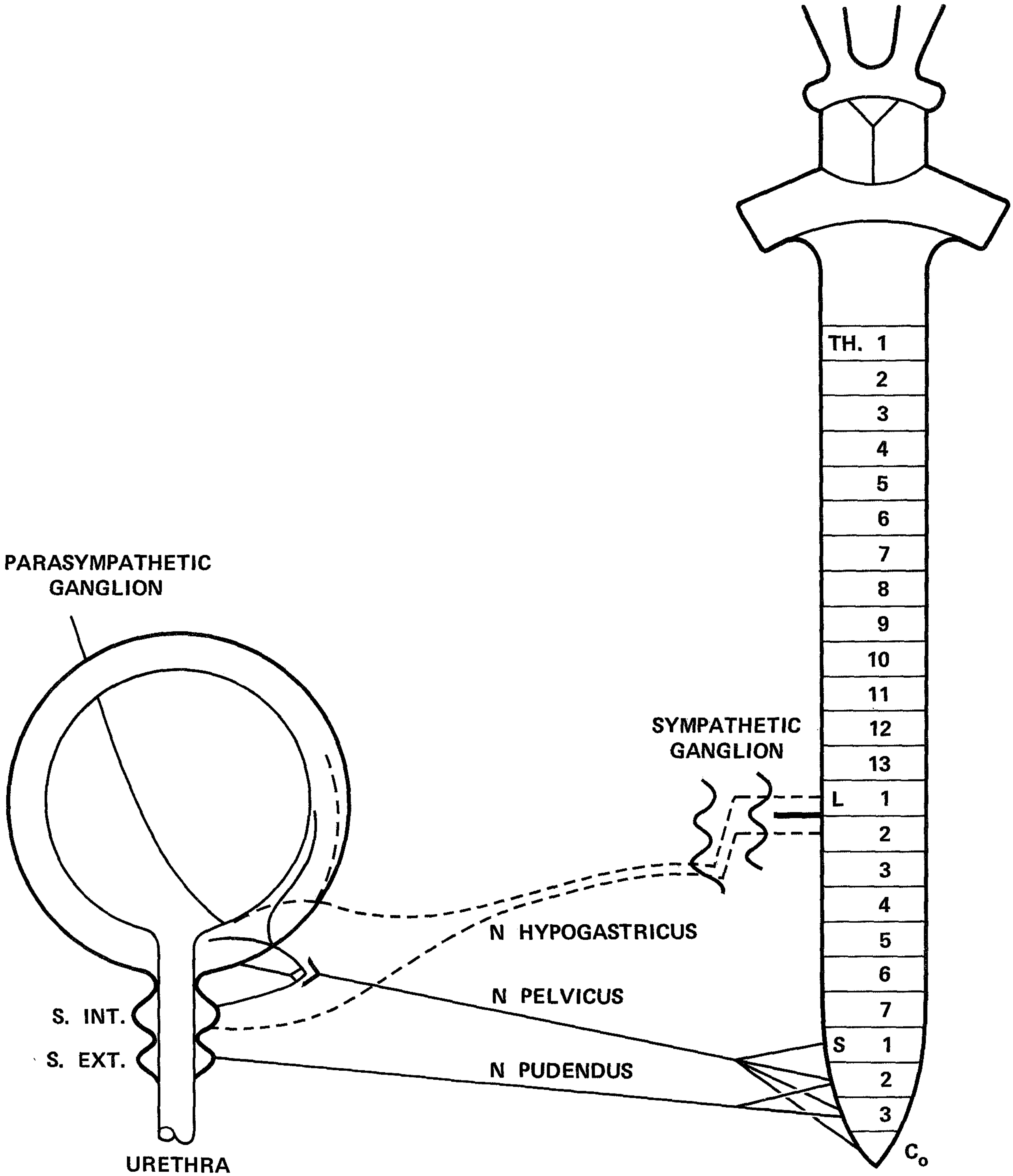

Fig. 10-2.– Diagram of spinal cord-bladder functional connections in the dog (adapted from De Jonge).

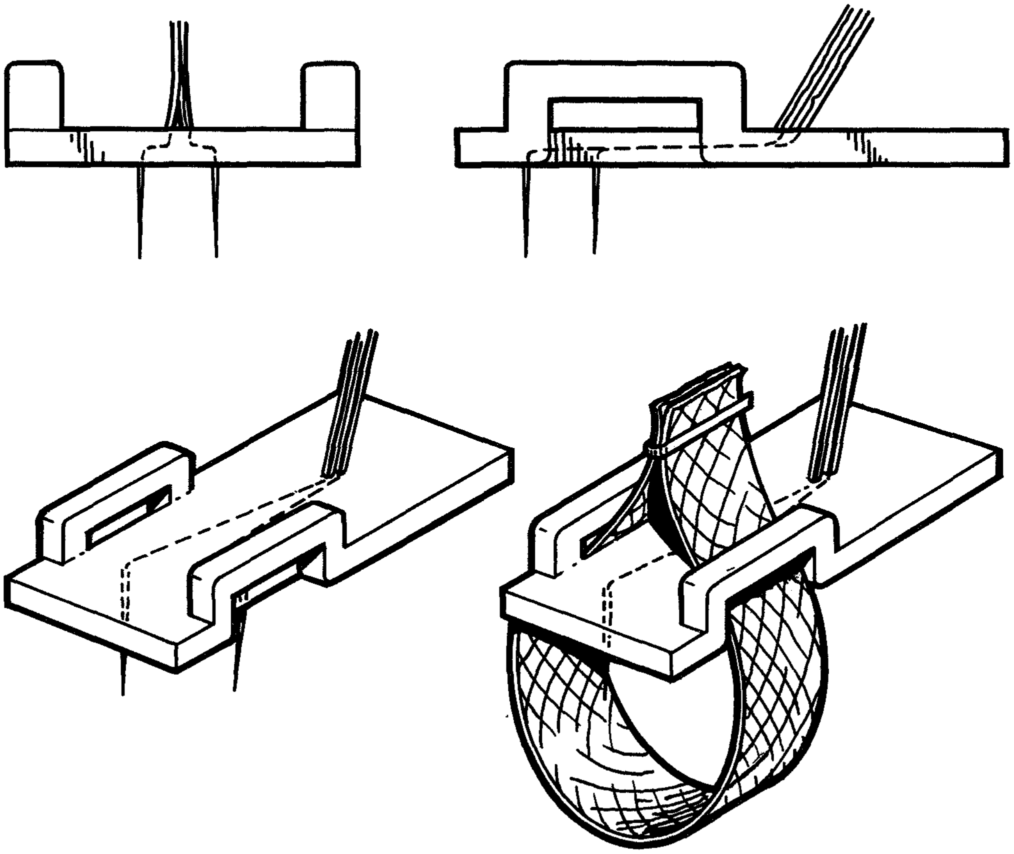

Fig. 10-3.– RF electrode system for stimulation of the neural control center for bladder contraction.

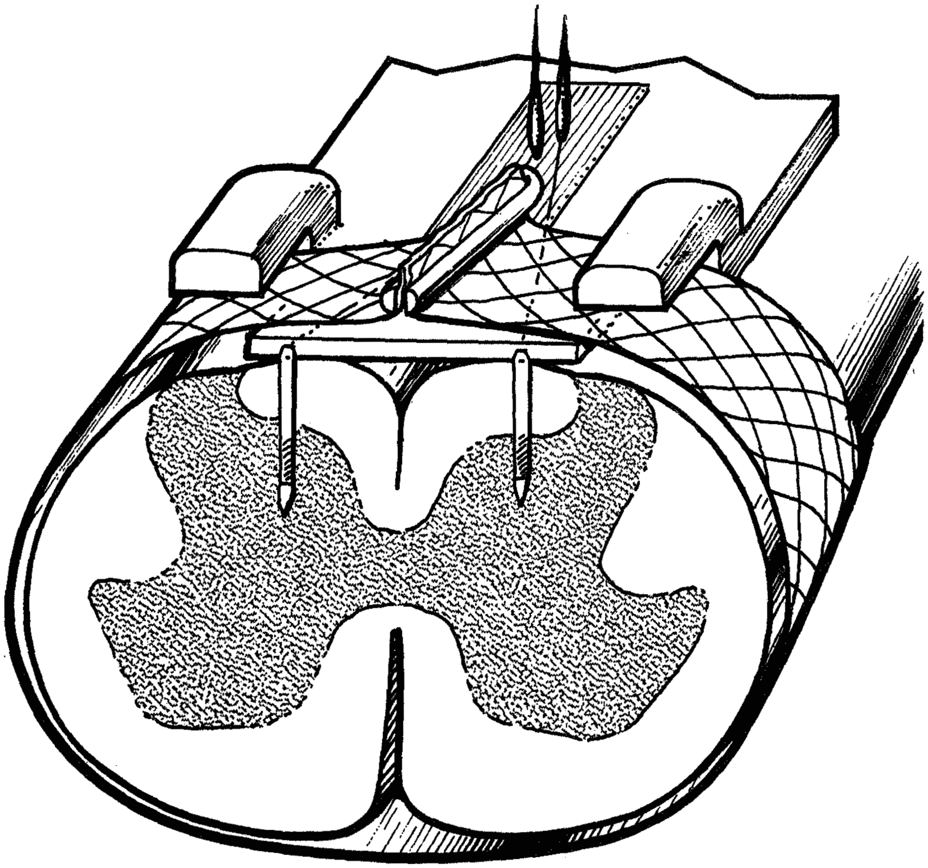

Fig. 10-4.– Implanted spinal neuroprosthesis.

Chapter 11

COPING WITH BRAIN DAMAGE

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In this chapter, we will discuss two neurological disorders: cerebral palsy, and traumatic brain damage as from an accident. The discussion will cover the incidence of disabilities, their characteristics, and what is now being done to deal with them, particularly in reference to areas in which the capabilities of the engineer can be effectively applied. For simplicity, some of the medical aspects are omitted.

Disabilities such as these occur in a continuous spectrum from the obvious severe abnormality to apparently normal, or very nearly normal behavior. It is necessary to classify and to generalize, but you will find individuals between any clear classes that you can define.

CEREBRAL PALSY

The term *cerebral palsy* refers to a group of conditions characterized by a disorder of motor control originating in the brain. The disorder usually is considered the neurologic residue of brain damage or a nonprogressive lesion, and it occurs before, during, or within the first year after birth. About 6 or 7 children per thousand births are affected, and there are about 200 cases per 100,000 population. The total number in the United States is about 750,000 young people.

Classifications and Terminology

In classifying the various clinical observations, there are several characteristics to be considered. One way to group them is by the *neurologic symptoms* – spasticity is a frequent characteristic. Alternatively the child may show uncontrollable, involuntary, and uncoordinated motions, either writhing or sudden and jerky motions. He may overshoot and vibrate around something he tries to point to or something he tries to touch. A single type of abnormal behavior may predominate, but there usually is evidence of more than one kind of disorder.

A second classification is according to the *areas* of the body involved – designated by the terms *paraplegia, hemiplegia, quadriplegia, triplegia,* and various others. Spastic diplegia is common in cerebral palsy that primarily involves the lower extremities, but the arms show some losses as well.

A third kind of useful classification is the *severity* of the involvement: *mild* if the child is able to ambulate, to use his upper extremities, and to speak well enough that he requires no special care; *moderate* if he is handicapped in locomotion or self-help or communication; and *severe* if he is bedridden or restricted to a wheelchair. Of course, these conditions and characteristics are not really static. The child is growing and developing, and some days he is better than on others. These definitions are useful if they are not applied too rigidly.

Two Examples of Cases

An infant may have excessive activity of the adductor muscles pulling the legs together, which tends to cause a hip dislocation by forcing the femur out of the socket. A brace may be used to hold the legs apart or surgical release may be necessary. The same excessive adduction and hip flexor spasticity contribute to the scissor gait characteristic of many such children. Another characteristic beyond the adduction compounds the difficulty – the involvement of two of the well-known reflex patterns. One of them is the automatic response called the *positive supporting* reaction: when you touch something with your foot, the leg and the ankle are extended to support the weight. The other is a somewhat contradictory response pattern, the *avoiding* response, whereby the leg or the arm pulls away from a noxious stimulus. Some of these reflexes themselves involve the action of the adductor muscles, and a conflict develops.

Thus, in addition to the specific muscles with spasticity or the specific overbalance of one group of muscles versus another, there are characteristic patterns of response that are grouped as the attitudinal or the postural reflexes, and these provide still another way to analyze the behavior. A normal child exhibits these response patterns at particular ages, but they are gradually absorbed into his voluntary patterns of motion as his cerebral control develops. In some respects, the child with cerebral palsy may be considered to have a neuromuscular system that does not mature as rapidly as normal; in fact, it may never completely mature. One of the questions is, what apparatus can be built that can use such patterns or can negate them effectively and constructively? How do you stimulate or inhibit stimulation to aid the child to develop or at least to function more effectively at his current stage?

As a second example, the child may lack control of muscles involved in speech. Because he cannot answer questions or talk at a normal age, in earlier years he would have been thought to have been mentally retarded; in many cases, there *is* mental retardation. Often, however, such a child is found to have normal or above normal intelligence when special teaching techniques are used that enable him to respond in ways over which he has control. Special treatment or easily used controls can be and have been built for such children.

Needs of the Patient

What does a child really need in such a situation? Medical support and stabilization would appear to have primary importance. This may include reconstructive surgery or bracing or medication to prevent seizures. Second, he needs a means of communication. Where speech is not possible, his response can be by eye or facial motions, or by hand movements, even erratic ones, on a key or a lever of special equipment or of a typewriter; and the child should be enabled to initiate remarks – not simply respond to other people saying things to him. Third, the youngster needs a stability of position – a way to sit or stand comfortably – in a position suitable for doing things that he is interested in. Fourth, he needs a means of mobility. Some children are involved so severely that they cannot crawl or even turn over. Sometimes, special scooters or supports can enable them to use such controlled motions as they have to get from one place to another. Equipment of this kind seems useful in training them in coordinated motions so that they can improve their function. Finally, they need a means of manipulating the environment around them so that they can pick up and release toys, move levers on equipment, turn the pages of a book, or even feed themselves.

Each of these aids is valuable not only for the improved function of the child, but also because of the gain in morale, interest, and motivation that accompany the new functional ability.

Examples of Assistive Devices

One means of correcting the characteristic scissors stance of a child, as in the first example above, is a hip action brace. This brace is an ingenious development that permits the motion of the legs apart, the motion of the hips forward and back, so that the child can walk, but it does not permit the legs to come together. It is particularly effective with younger children. You have to be careful in bracing, however. A brace is functional, but we tend to build a lot of hardware, and put it on the child in such a manner that the hardware stands by itself and the child can't do a thing in it.

A head support is a partial solution to another kind of problem. A child may have weak neck muscles or lack of control so that he can't hold his head up, he can't do any desk work, he can't do tabletop activities, and it may even be difficult to feed him. Some way to hold his head in position is very useful, but current devices tend to permit only limited movement.

Figure 11-1 shows a type of crawler that supports the child's weight and where he has enough motion of arms or legs, he can push himself around. This is similar to the type of device discussed by McLaurin (Chap. 6).

The crawler or scooter shown in Figure 11-2 promotes upper extremity development, and the reciprocating pattern of the arms.

Figure 11-3 shows a safety walker with four casters on the bottom, which make it very easy for the child to push around. But if the child starts to fall, or stagger, or go too fast, the excess weight on the top immediately brings the rubber bumper at the bottom into contact as a brake and stops the equipment, so the child doesn't fall. This device has worked very well for some children who were not able to walk in other ways.

A training bicycle, shown in Figure 11-4, is for a child who has some leg thrust but not the reciprocal motions of the feet. The legs are strapped in and the wheels are driven by an electric motor. The idea is to train him in patterned activities, so that he can make an effort and eventually learn the reciprocal motion that is needed for both crawling and walking.

Many other devices have been built at a number of centers for the aid of children.

Areas for Study

Where can the engineer contribute his talents and his technology? More attention is needed in many areas. We still need a great deal in the way of improved assistive devices, both the *passive* for positioning and the *dynamic* for functional use. Head positioning is not yet adequate. Damping the erratic motions of the upper extremity is needed, and improved communication with the affected child. Better evaluation of assistive devices is needed. Measured objectively, how much do they really help? How do they affect the child's growth and maturation, if at all? What special training devices and techniques can be developed and used? How can such devices be built so as to be inexpensive, yet versatile enough to meet the various needs of various different children and maybe the various needs of different therapists or different schools of therapy?

Can the particular deficit of a particular child be more clearly diagnosed, the trouble located more precisely, and some way around it devised or some supplemental connections be made in the deficient neurological net? These questions involve rather sophisticated neuroanatomical considerations, and are left to other discussions.

TRAUMATIC BRAIN DAMAGE

A blow to the head may be severe enough to cause brain damage and even to fracture the skull. If the victim is not killed, the general idea is to assist in as complete a recovery as possible. How common is this sort of injury?

It is estimated there are about 3 million head injuries and skull fractures each year in the United States. About half of these are severe enough to restrict activity; between a quarter and a third – about 875,000 each year – are severe enough to disable a person. Of these more serious ones, about half occur among young people under 17 years old. Again, it is a significant proportion of younger people.

Characteristics of Trauma

The commonest symptom of head injury is a disturbance of consciousness. Coma may be brief, or in more severe cases it may last days or weeks. When consciousness is recovered, patients with a minor degree of concussion – that is, no significant structural damage to the brain – may be normal within a few minutes. Others may be slightly dazed for a few minutes and have headaches for 12 to 24 hours. And with the more severe forms of damage there may be persisting headaches, dizziness, continuing mental cloudiness or confusion, and other symptoms mentioned earlier. There is improvement with time, but there may be permanent residual mental damage.

Treatment

Medical, perhaps surgical, care is needed in the initial acute phase, and the patient must be kept quiet. When the patient regains consciousness, the chief function of care is to assist and encourage redevelopment by providing increasing amounts of activity – training in motions, body control, and speech, as appropriate.

So what does the person need? Well, as in the case of cerebral palsy, the victim of trauma needs medical stabilization, communication, positioning, mobility, and manipulation of the environment. In particular, the complex loop of visual or auditory stimuli – the reception, the decoding, the response, and the expression of the response – may be damaged at any of these stages. It may require skillful testing to locate the damage and to establish a program to redevelop this facility.

The extent to which technology can aid in the treatment of traumatic brain damage is an open question. Improvement is spontaneous, and training may or may not accelerate it. This is a debatable area. It may be worthwhile to develop programmable equipment to provide auditory, visual, and perhaps other stimulation, together with the measurement of response from the patient. The idea would be to get him in contact with the external world again, and much of this treatment, now done by people, could be done by machine. Some repetitive training tasks could be made more automatic. But I suspect that much of the benefit of therapy in recovery after coma lies in the personal relationship of the therapist or the physician with the patient, so that efficient automation is not necessarily the most effective treatment.

Prevention

Many cases of traumatic brain damage occur in automobile accidents, some in sports. With automobiles, the importance of safety design has been recognized, and, of course, it should be extended. In sports, attention has been given to the design of protective equipment, such as football helmets. One of the questions is, how much shock can the head stand without damage? According to some studies, most people can tolerate up to about 80 G with little or no damage. Concussion may occur with the application of 95 to 115 G, and a linear fracture in the human cadaver may be seen with the application of a 200 G peak value. But these cases involve direct blows with a blunt instrument. Telemetered accelerometer studies at the University of California at Davis have shown that in a normal football game the athlete's head may experience as much as 1,000 G peak linear accelerations with no ill effect – with present protective equipment. So perhaps the most fruitful area for engineering is in the measurement of accident processes, the design of safety equipment and procedures, the training of personnel, and evaluation of the program to determine its long-term validity.

Areas for Study

Engineers with an interest in systems analysis or communication networks might contribute usefully in the study of structure and function of the brain. One could start with the Michigan report on the central nervous system as a network; the best available information is presented on 418 selected, specific centers in the brain. But there are at least three reasons why this is too simple-minded an approach: (1) Only nerve connections are included, and it is well known that there are functional loops involving chemical transmission as one step in the loop. (2) There is an effect on functioning of previous "set" or attitude. Even the order in which a signal passes from one part of the brain to another and on to a third may be different under different conditions. (3) The chart itself, as the authors point out, is the first rather than the last word on the subject. Many links are uncertain and many are doubtless yet to be discovered and proved. However, it appears that the communications systems approach might suggest some useful experiments for a psychophysiological laboratory and might lead to better techniques for retraining neuromuscular and even mental functions.

Fig. 11-1.– A crawler to support a child's weight and facilitate movement.

Fig. 11-2.– Crawler, or scooter, to promote upper extremity development.

Fig. 11-3.– Child's safety walker.

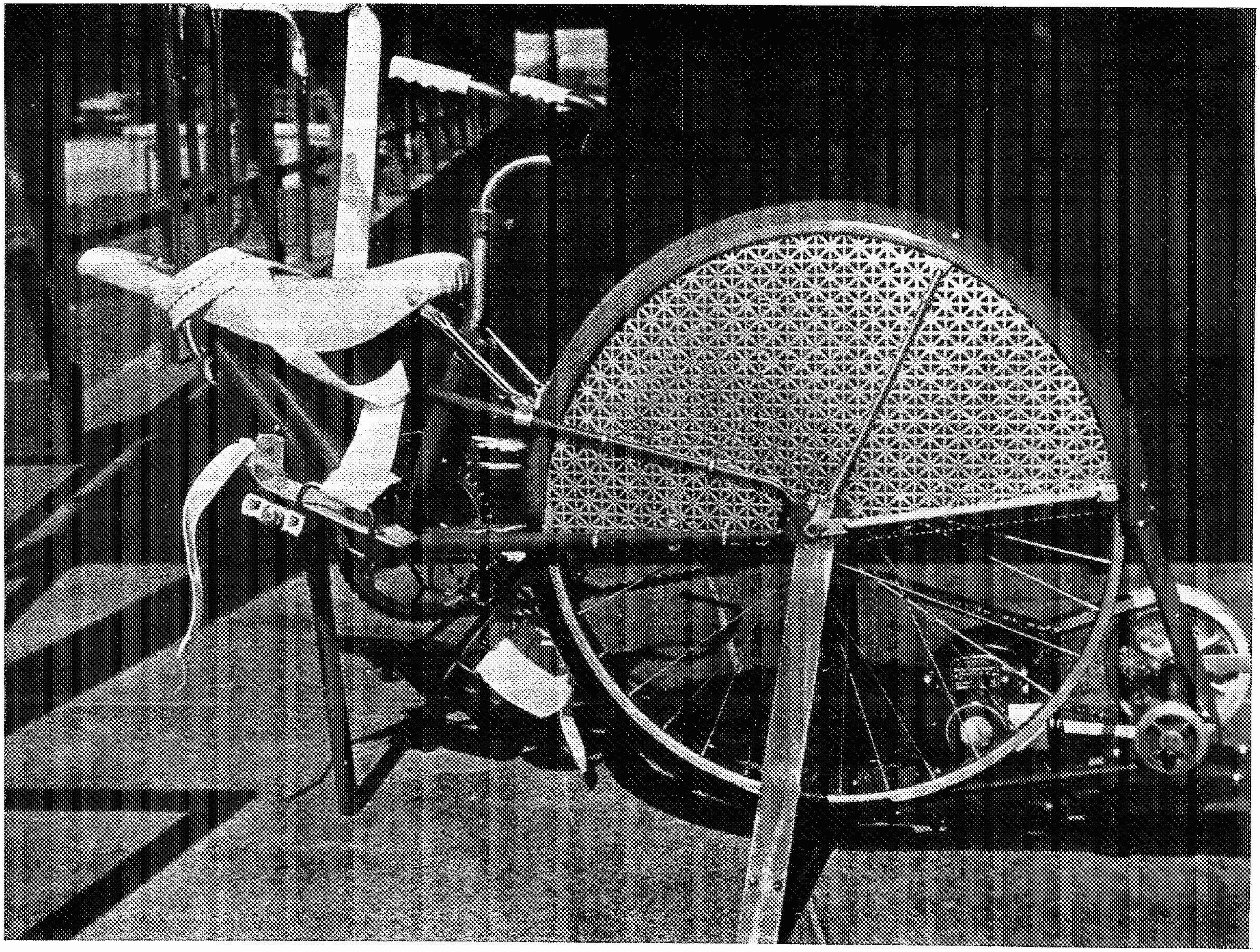

Fig. 11-4.– Training bicycle for patterned activities.

Chapter 12

BLINDNESS

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In recent years, there has been a progressive expansion of the interface between technology and medicine, particularly in cardiovascular research. However, nowhere is it more exciting to consider the possibilities that modern electronics and engineering have to offer than in the individual with a damaged or disordered nervous system, especially the blind person. In this chapter, we discuss the incidence and principal causes of blindness, outline some past research activities, and present a capsule review of some of the more interesting programs designed to provide the blind with the ability to be mobile in their environment and to read printed matter.

INCIDENCE AND PRINCIPAL CAUSES

The term *blindness* is not synonymous with total loss of vision. It includes individuals with a severe impairment of vision. In the United States, persons are considered legally blind if their visual acuity is 20/200 or less in the better eye etc. at the widest diameter of the field of vision but with an angle no greater than 20° (in some states this is 30°).

There are approximately 450,000 legally blind persons in the United States. Of these, 9 percent are under age 20; 13.5 percent are age 20 to 39; 29.5 percent are age 40 to 64; and 47 percent are over age 65. Unfortunately there is no accurate analogous information on the causes of blindness in the United States. Detailed medical records are not commonly available on the causes of blindness. Data from the Department of Health, Education, and Welfare indicate that the most common causes are generally diseases, particularly diabetes and vascular diseases. Blindness due to prenatal influence accounts for about 16.7 percent; senile cataract, 15.6 percent; and glaucoma, 13.5 percent. And there are many other categories.

Blindness in the diabetic is due primarily to a retinopathy. Most cases due to vascular disease are the result of retinal degeneration, particularly in the region of the macula, which is the focal point for light in the back of the eye. The prenatal category includes congenital malformations of the eye, such as coloboma and absence of all or part of the eye, congenital cataracts, and glaucoma, albinism, and various types of hereditary retinal degeneration.

Causes of total blindness are injuries (23 percent), tumors (23 percent), infectious diseases (12 percent), and miscellaneous (42 percent). It is important to note that 68 percent of the totally blind are under 65 years of age, and 55 percent are less than 45 years of age. Enabling these handicapped persons to function better and become independent economically offers a real challenge.

DEVELOPMENT OF SENSORY AIDS

Throughout the years, particularly recently, technology has been brought to bear on the problem of blindness in many ways. Numerous devices have been designed and fabricated to enable the blind to move about more safely and to read. Time does not permit more than a brief description to some of the more important work. Nye and Bliss prepared excellent reviews of the subject, which appeared in the *Proceedings* of the IEEE in December, 1970. Bliss discusses some of these approaches in Chapter 16.

Past and present programs to provide sensory aids for the blind can be divided into three categories: mobility aids, reading aids, and visual substitution systems. As long ago as 1912, Fournier D'Albe invented the exploring optophone. Ambient light activated selenium cells connected in a Wheatstone bridge to periodically interrupt the current and generate a buzz in a pair of earphones.

By 1923 Miss Mary Jameson, using an optophone modified to give information about the black and white characters constituting a printed page, was able read "At speeds of 60 words per minute." Unfortunately these reading rates were obtainable by only a small number of people.

Mobility Aids

Since the mobility aid that is most popular with blind people is the cane, efforts have been made to improve rather than replace it. One such device currently being developed and tested is the bionic laser cane, which incorporates three optical ranging systems. One system detects objects straight ahead, another overhead, and the third samples the walking surface. All three of the receivers operate a single tactile stimulator in contact with the index fingers. In addition, a small loudspeaker in the hand emits a high -pitched sound when an overhead obstacle is encountered, no sound for a forward obstacle, and a low -pitched tone for surface hazards.

Ultrasonic spectacles designed by Kay of New Zealand use an ultrasonic sonar system with transmitters and receivers located at the bridge of the nose. The received echo is mixed with the transmitted signal, which is conveyed to the user through earphones. The time of arrival and intensity of the signal indicates the location of the reflecting object.

A third device, the travel path sounder, also operates on the ultrasonic beam auditory principle. It explores the area through which the user's head and shoulders will pass in the next 6 feet. If no obstacle is present, no sound is heard. However, when an obstacle is present, a ticking sound is broadcast, which grows in intensity until at a distance of 30 inches it changes to a beeping sound.

Reading Aids

Braille reading has been used by the blind for more than a century. However, contrary to public opinion, it is used by no more than 10 percent of blind persons. Efforts are being made to improve the quality and availability of Braille by storing it on punch paper or electromagnetic tapes and using these in turn to activate an array of electromechanically energized pins. Computer translation of Braille is also being investigated.

A most useful device for the partially blind person is an electronic image intensifier. This consists of a television camera and monitor, which provide an enlarged high contrast image of the printed page. The majority of persons tested have been able to read or write with this system.

A family of devices that convert print into either tactile or auditory displays have been designed and are currently being investigated. These reading aids and present recognition machines are discussed in Chapter 16.

Visual Substitution Systems

There are two kinds of visual substitution systems; one is based on direct electrical stimulations to the visual pathways, excluding the retina and the optic nerves and tracts, and in the other, skin replaces the retina as a primary sensor receptor. Starkiewicz and Kuliszewski of Poland have devised the elektoftalm in which a grid of 120 photoreceptors is connected to a corresponding array of tactile stimulators laid against the patient's forehead. The authors report that after several weeks of practice, a blind person can sense and avoid white objects in a black room; he also can recognize and identify letters and simple symbols displayed on contrasting blacks and whites before him.

Another tactile substitution technique is the television system devised by Bach y Rita and his associates in San Francisco, who use the skin on the patient's trunk to register light stimuli. A Vidicon camera converts the optical into a tactile image displayed by an array of 400 oscillators in a 20-by-20 matrix on the patient's trunk. We understand that they now are using electrical stimulation and extending it from the back on to the abdomen. After as little as two hour's practice, their patients are able to recognize with a single scan of the camera words of five and six letters with an accuracy of 80 percent. After four hours of practice, they are able to identify real objects, such as chairs, telephones, and a statircase, and also to recognize and read block letters.

The project of particular interest to our group and others is the restoration of "vision" to the blind by direct stimulation to the visual area of the brain. It has long been known that phosphenes are produced by electrical stimulation of the optic nerves and tracts, the optic radiations, and the visual cortex. Phosphenes are subjective visual sensations that do not depend on stimulation of the photoreceptor cells in the retina. The word *phosphene* is derived from the Greek *phos* (light) and *phainein* (to show). Most people are familiar with the sensation of seeing stars following a blow to the head. An easily induced example of a pressure phosphene is the visual sensation that you will have when you apply simple pressure to the globe of your eye.

ELECTRICAL STIMULATION OF THE VISUAL CORTEX

The history of electrical stimulation of the visual cortex is most interesting. In 1929, Otfried Foerster of Breslau reported his experience of electrically stimulating the occipital lobe of a patient under local anesthesia. He found that stimulation of the extreme pole of the right hemisphere was followed by the patient's sensing a light in the center of the field of vision. When he stimulated a point on the calcarine cortex, which is the inside portion of the occipital lobe, the patient experienced a light in the opposite field of vision.

In 1932, Krause and Schum reported a similar procedure performed on a patient who had been blind for 8 years following a gunshot wound of the optic radiation. When the visual cortex was stimulated, the patient experienced a light in the opposite visual field, and for the first time it was noted that despite the deprivation of visual stimuli for a long period of time, the visual cortex of this blind person was functional.

Penfield and his associates in Montreal have carried out thousands of stimulations of the human brain during surgical procedures under local anesthesia. These have contributed significantly to our knowledge of brain function, but unfortunately their data on visual cortex function and localization are limited.

In 1957, Button and Putnam inserted electrodes at various depths into the occipital lobe of three blind patients. Various parameters of the electrical stimulation were used and their patients experienced visual sensations. Their third patient was a 48-year-old man who had been blind for 8 years (Fig. 12-1). By means of a photoelectric cell, which he held in his hand, he was able to follow a flashlight held 15 feet in front of him and could also identify a window through which the sun shone.

The work of Brindley and Lewin has given impetus to the present research efforts to produce a visual prosthesis. As noted by Hambrecht (Chap. 7), they placed an array of 80 electrodes on the calcarine cortex of the visual area of the brain of a blind 52-year-old woman (Fig. 12-2). The leads from these electrodes were connected through a small opening in the skull to 80 radio receivers implanted beneath the scalp. From transmitters appropriately tuned to the frequencies of the individual receivers, radio signals selectively activated the cortical electrodes. Data obtained indicated that by programming the stimuli, it was possible to generate simple predictable patterns with four or five electrodes. With variations in the parameters of stimulation, phosphenes persisted up to 2 minutes after the stimulation ceased. In the 4 years since the electrode array was implanted, Brindley's patient has suffered no untoward effects from the total stimulation time of over 300 hours, although only 10 electrodes are still functioning.

The experience of Brindley and Lewin stimulated workers in this country to determine the feasibility of restoring vision to the blind by means of patterned electrical stimulation in the visual cortex. During the past 2 years, a visual prosthesis program has been supported and coordinated by the National Institute of Neurological Diseases and Stroke. Research teams at Johns Hopkins University, Harvard University, University of Rochester, University of Utah, and our Institute are engaged in exploring many of the facets of the problem. These inclue (1) tissue reaction to a large number of biomaterials that would be used in the fabrication of either electrodes or electrode arrays; (2) the effect of electrical stimulation on the blood brain barrier as well as the underlying brain; (3) behavioral studies in primates subjected to visual cortex stimulation; and (4) stimulation of the human visual cortex and visual pathways in selected cases at the time of surgery or postoperatively using electrode tresses extending from the striate cortex to the thalamus or by the use of electrode arrays incorporated in surgical drains.

While most of the studies are still in progress and much of the data are preliminary, some of the findings are worthy of mention. The findings of Dobelle and his associates at the University of Utah are of particular interest. These investigators have collaborated with neurosurgeons throughout the country in stimulating the visual cortexes of 18 patients operated on for such lesions as tumors, arteriovenous malformations, epileptogenic foci, hydrocephalus, and subdural hematoma. They have investigated many stimulus modes and parameters. Their results suggest that a clinically implementable prosthesis will have to be restricted to stimulation of the striate cortex.

When they stimulated the occipital pole or the mesial surface of the occipital lobe, they obtained phosphenes from 90 percent of the points stimulated. In contrast, when they stimulated on the lateral surface of the occipital lobe and so-called areas 18 and 19, they got phosphenes in only fewer than 10 percent of the patients. They comment that if intracortical stimulations could be used – that is, if electrodes could be placed in the brain itself – the threshold for stimulation would reduce as much as three orders in magnitude – from 2 or 3 ma, which in general has been found necessary to produce a phosphene in a patient, to 2 or 3 μa.

Additional studies on stimulation of the visual system are being conducted by investigators at Harvard and Johns Hopkins. Walker and his associates at Hopkins have stimulated the optic radiations at various depths, using electrode tresses, and have evoked phosphenes that are complex both in the form and color. Doty and his co-workers in Rochester are conducting behavioral studies on monkeys subjected to stimulation of their visual cortex.

Our group in Pasadena has been concerned with the effect of current density on the blood brain barrier and the cerebral cortex of cats. In one phase of this project, acute and short-term experiments have been carried out; in another long-term study, we have implanted electrode arrays and subjected the animals to daily stimulation using various stimulation modes and parameters. The goal of this project is to find safe, yet effective, techniques of electrical stimulation.

We have used the blood brain barrier breakdown as an index in determining when we have caused some degree of injury to the underlying brain. The animals are given Evans blue, an intravital dye that does not go into the brain under normal conditions but only with breakdown of the blood brain barrier – the barrier that prevents drugs, toxins, and other things from getting into the nervous system. We have taken pictures of this work through a surgical microscope.

Figure 12-3 shows a very early lesion; the dust may be a little bit of bone dust. The slight discoloration of the brain is believed to be the first indication that we have caused injury. Now, our experience suggests that if we have stopped our electrical stimulation this much damage is reversible and would heal, and we probably have not injured the underlying nerve cells concerned with vision.

If we go a step further, you see not only the discoloration, but also thrombosed blood vessels (Fig. 12-4). Some of the arteries and veins are interrupted. This we believe is an irreversible lesion that will heal, but only at the cost of damage to some of the underlying nerve cells. If we use monophasic direct coupled stimulation without a capacitor, we generate a violent foam, and this obviously is a type of stimulus mode that should be avoided.

We have tried both direct and capacitatively coupled monophasic and biphasic stimulation, with reasonable stimulation parameters. At this point, we have not found any safe stimulus that can be continued for 15 minutes or more.

In Nashold's work on effective emptying of the urinary bladder, a stimulus is only applied for less than a minute (Chap. 10). A visual prosthesis, however, might need to be operational as long as perhaps 16 hours a day.

We also have stimulated the visual area of human volunteer patients daily on the first three or four postoperative days using a Penrose type of drain, which incorporates an array of platinum electrodes. Our human data are limited at this point, but as we continue, we hopefully will gain answers to questions concerning such important points as pattern recognition and reproducibility, as well as the optimum location, configuration, and spacing of electrodes.

We are working with Frank and Hambrecht at NIH and others in an effort to devise a better type of array of electrodes that we can leave in our human volunteer patients.

Figure 12-5 shows one such array being implanted on the tip of the occipital lobe. The drain comes out over the surface of the brain to the connector.

Figure 12-6 shows the apparatus used in determining at what location in his field of vision he sees phosphenes. The bowl is 42 inches in diameter (a skylight that was sandblasted) and our coordinates are on the outside so that we can quickly spin them and determine exactly where the phosphene is. The patient looks down the bore sight, sees a small light, and then points out into the bowl perimeter and indicates where the visual sensation is.

Figure 12-7 shows a patient in bed postoperatively with the bowl perimeter in the proper location, and our stimulating and recording equipment.

Although the neurophysiological and technological bases for the feasibility of a sensory prosthesis seem sound, formidable problems remain to be solved before we will have a prosthesis that will enable the blind to move about safely in their environmental space and read print and handwriting at speeds comparable to the sighted people. It is apparent, for one thing, that we urgently need better methods of stimulation. Must it be electrical? Do we need better electrodes, better parameters, better techniques? At this moment in time, unless we solve these problems, the visual prosthesis is in hazardous territory.

It is obvious that there is flourishing interest in the problems of the blind, judging from the number of research programs and multidisciplinary conferences. While considerable progress is being made, we would agree with Nye and Bliss that much more could be gained with stronger and better coordinated efforts involving government, universities, research institutes, and industry. The sensory prosthesis project in the National Institute of Neurological Diseases and Stroke is a step in the right direction. Hopefully, this project might expand to include research programs with different approaches to the problems of the blind.

In a recent seminar, Derek Fender commented that the principal needs of a blind man are "A good woman and a long white cane." It seems to me that we should be able to provide more.

DISCUSSION

Q. One of the real things in this program is a challenge to the engineers and the people working in bioengineering. Brindley puts his first device in, it was almost, I guess, three or four years ago now, and he has been planning to put in successive devices since. He wanted to do one second model on a patient who is waiting and do the third model replacing the one that is now in. And the reason he hasn't been able to do this concerns our engineering problems in developing the electrodes and the devices that will withstand the biological environment through the spinal fluid and saline. So the development of these interface devices – the electrodes – is a real challenge to the engineering fraternity where the expertise of the neurosurgeons, neurologists, and neurophysiologists ends.

A. I fully agree. This is why we make a plea that we get back to discussing some of these problems. At every neurosurgical meeting I have attended to date, there has been an increasing interest in the techniques of not only stimulating the nervous system but also of blocking conduction. And in the world of the future I think the neurosurgeon is going to be largely involved with implantable devices to depolarize an epileptogenic focus (as Blain Nashold has done to stimulate the paralyzed bladder) to block pain, to provide movement where it doesn't exist, to control spasticity. You can go on and on and on. So we have to have some way of providing the optimum stimulus modes and parameters and having proper electrical materials that can be used for years and years and years.

So hopefully, before I leave here, we will have answers to some of these questions.

Q. Just a comment on the statistics of legal blindness. When the Institute first became interested in developing a visual prosthesis, we had several studies done in about 1966 or 1967. We have run a program for years, called the Model Recording Agency, which is now called the Fourteen States, really trying to get at the statistics of blindness and the causes of blindness. Both the Hamilton Standard Division of United Aircraft and the Travelers Institute Division of Hartford have examined all these things and concluded that the Model Recording statistics not only were good, but were the only ones that existed. They have done a lot of different kinds of correlation with the population groups, the age groups, and so on. At any rate, these two different groups concluded that these statistics were probably fairly reliable.

We have looked at IRS returns and they are useful, but they begin only with the legally blind. So that is a voluntary thing, and does not necessarily represent the true state of affairs.

A. The National Health Survey, which is based on door-to-door assessment techniques, doesn't involve ophthalmological examination, but nevertheless includes some tests of the ability of people to operate. The Survey arrived at an estimate of blindness of about four times 400,000. So with all deference to the Model Reporting Agency, I think there is reason to believe that the uncertainty is of the order of four or five in terms of the functional demography of the blind.

Fig. 12-1.– Button and Putnam's blind patient tracking flashlight with hand-held light sensor.

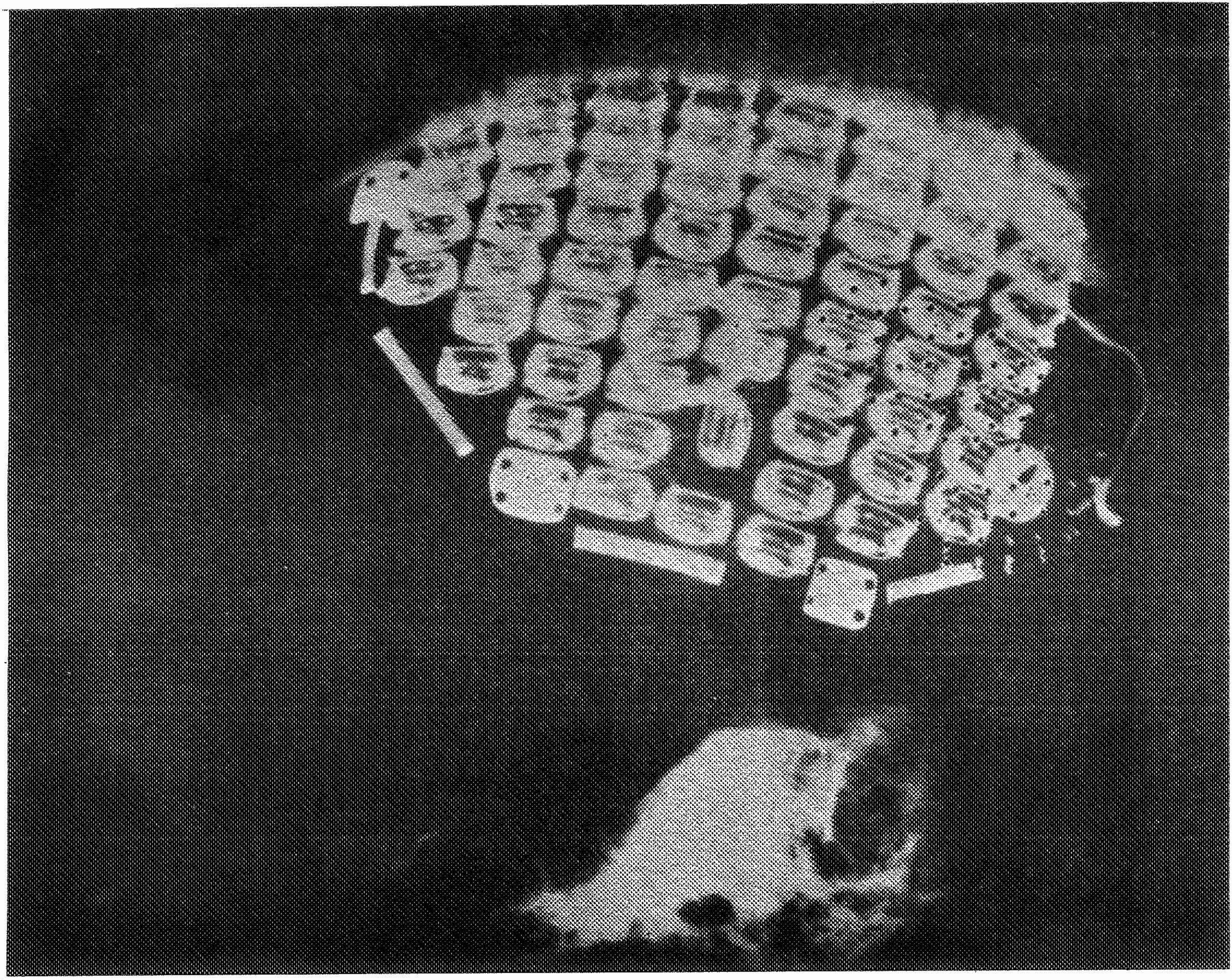

Fig. 12-2.— X-ray showing array of 80 radio receivers beneath the scalp of Brindley and Lewin's patient.

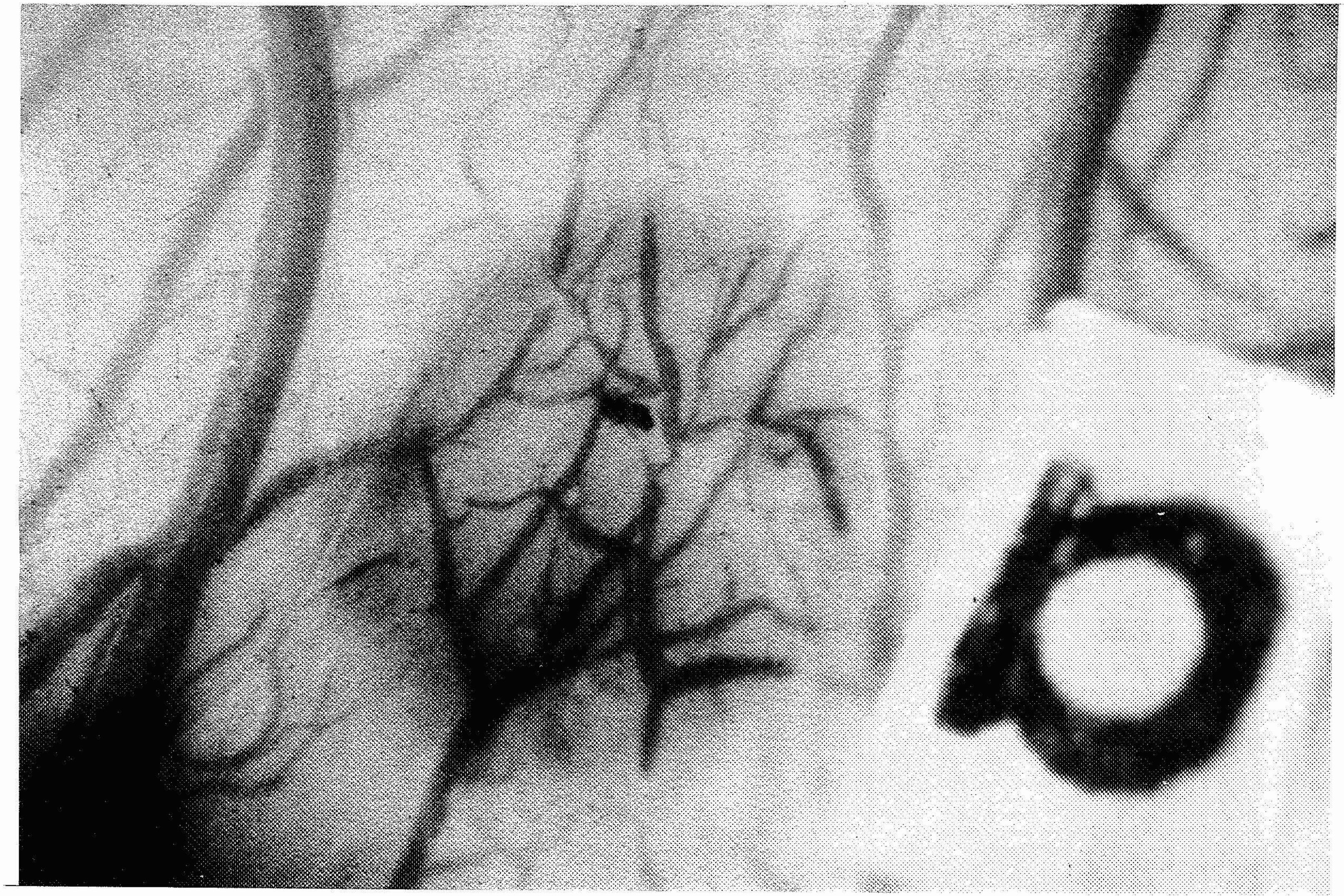

Fig. 12-3.— Diffuse ring stain of Evan's blue indicating breakdown in blood-brain barrier at site of stimulation on cat's cerebral cortex.

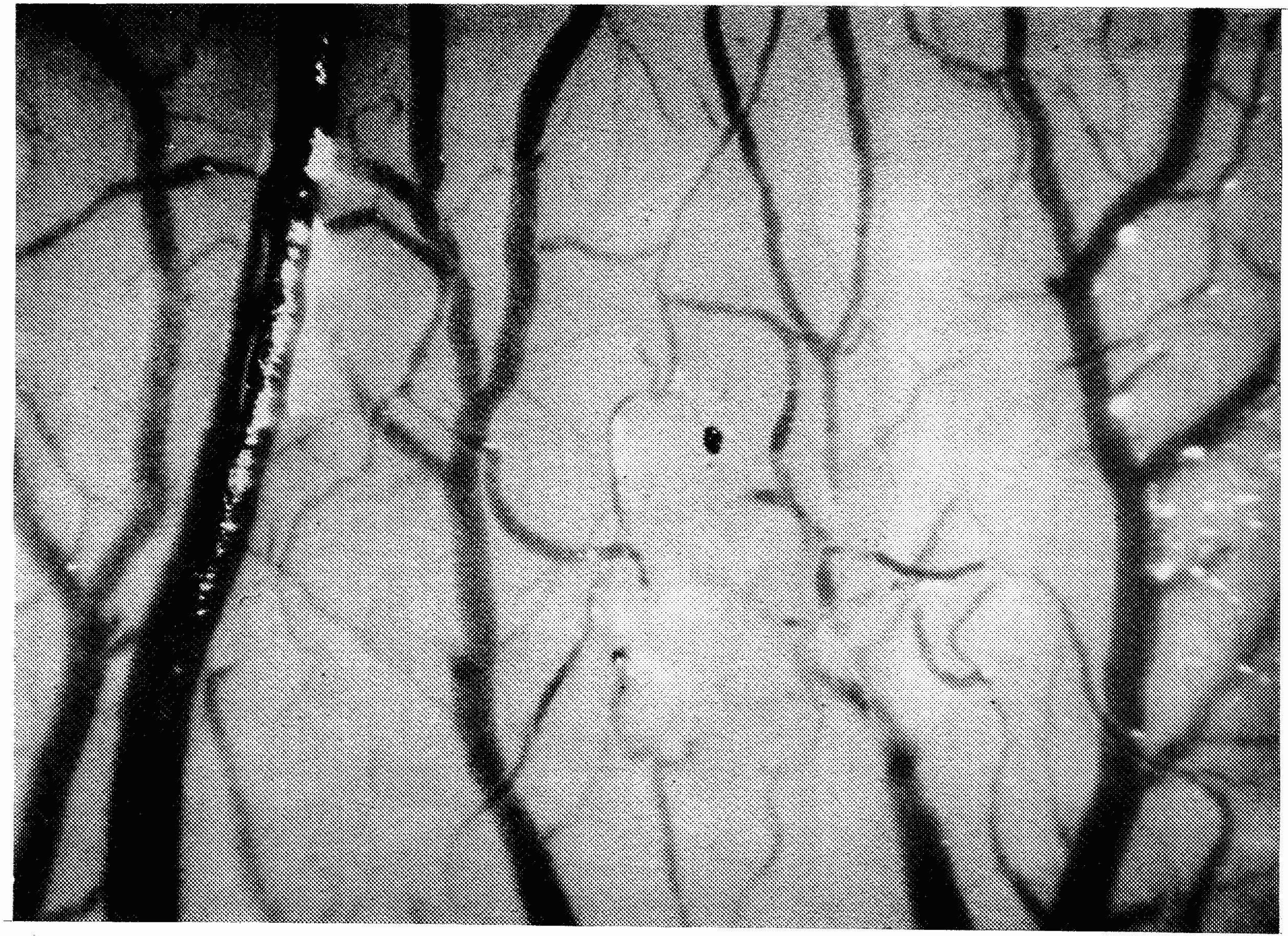

Fig. 12-4.— Spasm and thrombosis following surface stimulation of the cat's brain.

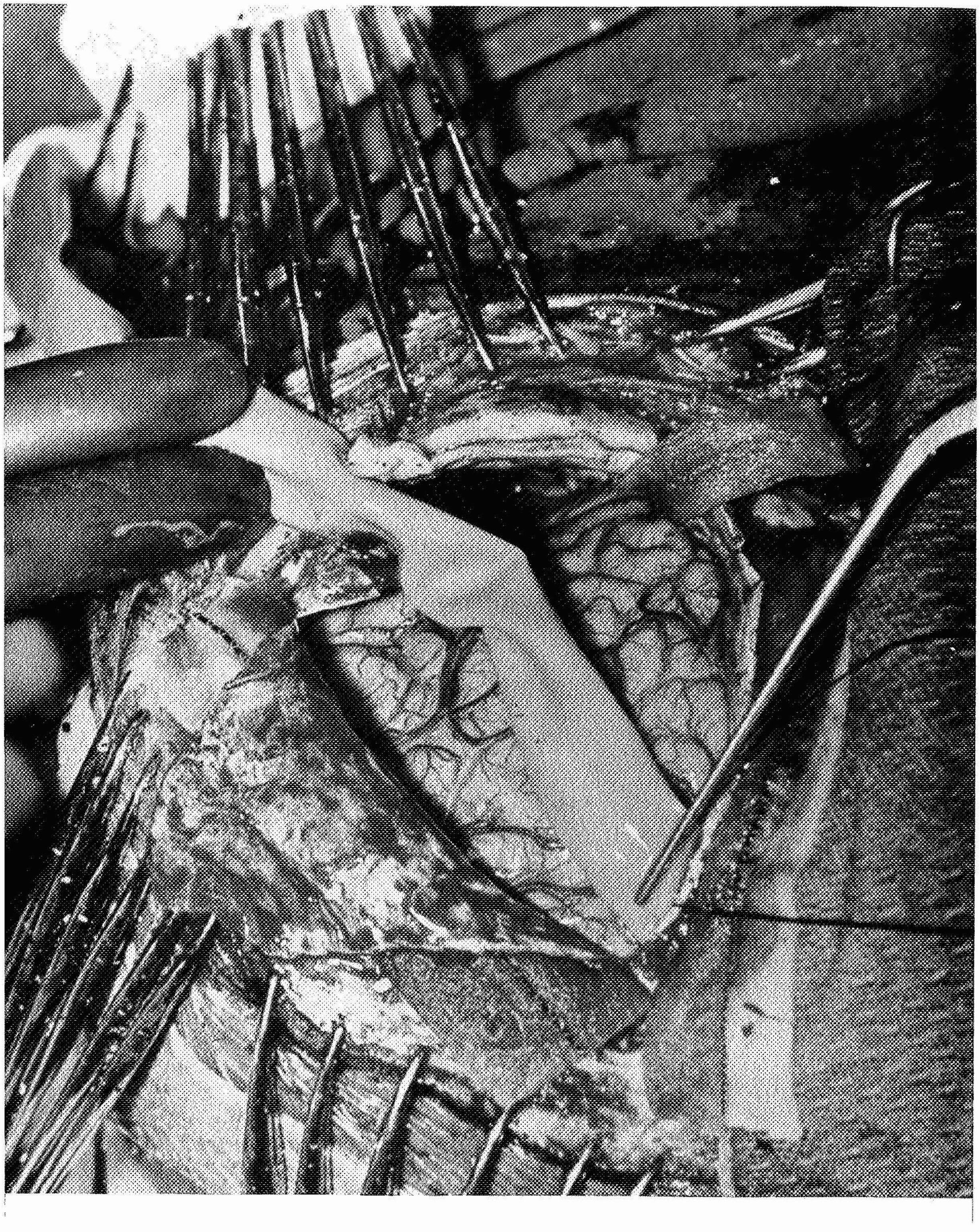

Fig. 12-5.– Implantation of electrode array on calcarine cortex after removal of a chronic subdural haematoma. Wires from the platinum iridium electrodes are contained within soft rubber drain held in forceps.

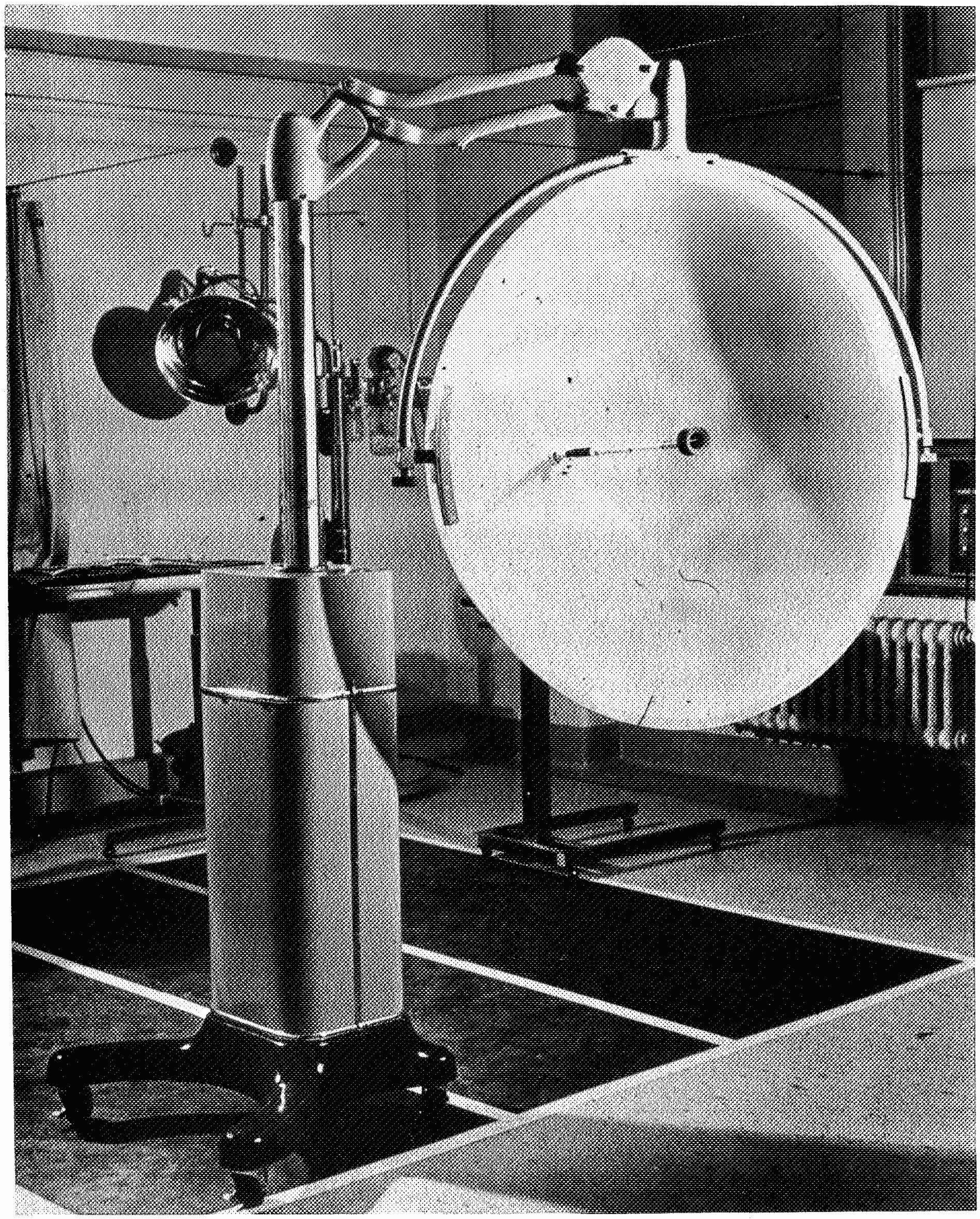

Fig. 12-6.– A 42-inch methyl methacrylate hemisphere mounted on an x-ray stand serves as a bowl perimeter.

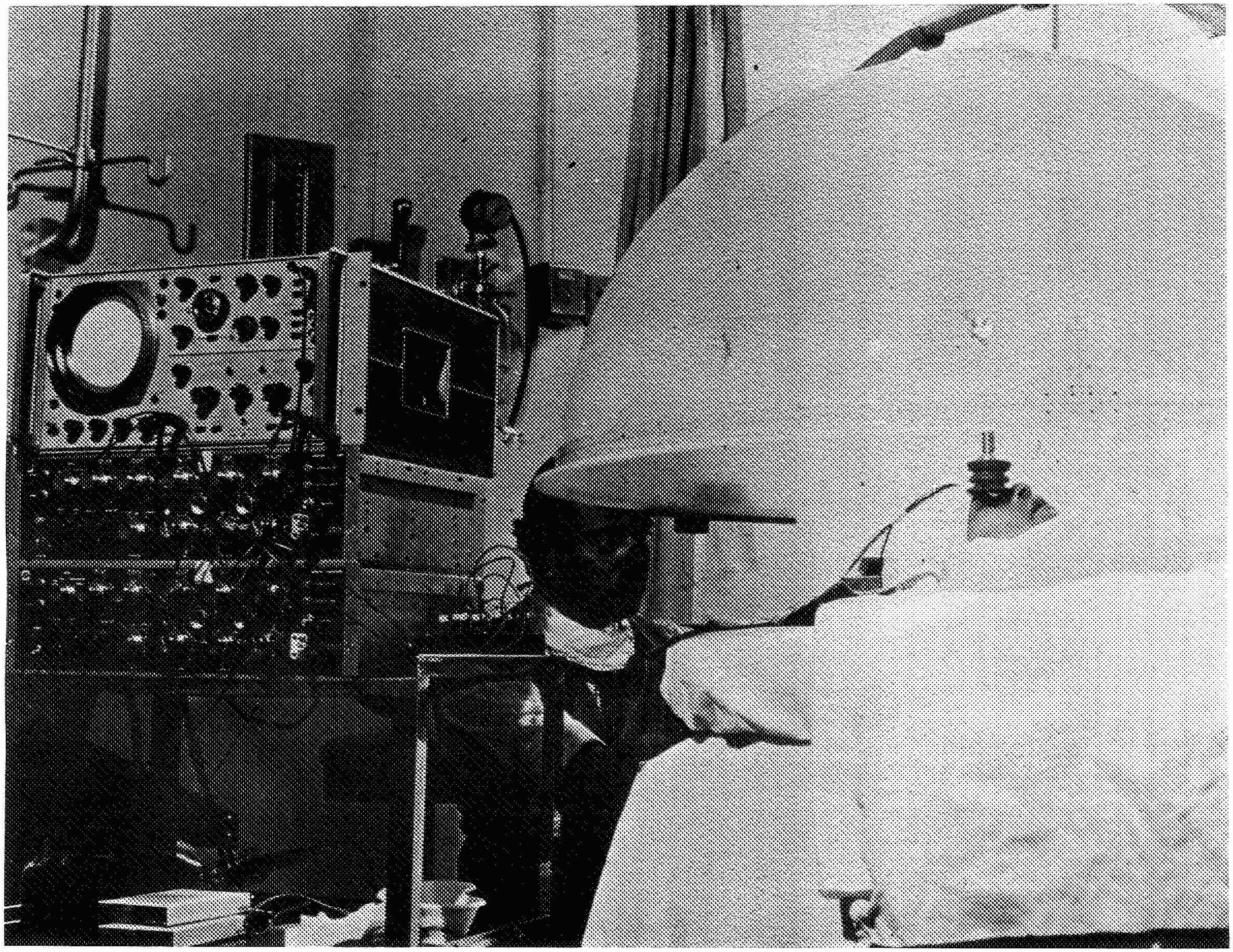

Fig. 12-7.– Bowl perimeter in position during a stimulation study of our second patient with an array of electrodes on right calcarine cortex.

Chapter 13

CYBERNETIC PROSTHESES

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Germeshausen Professor
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Ten years ago, John F. Kennedy threw a challenge to the American people to put an American on the moon in a decade! That was no insignificant challenge at the time, despite the realization now, 10 years later, of the orderly and regular process of achievement mounted by NASA. We are accorded striking evidence in Wyatt's discussion (Chap. 2), in which he noted the reduction in number of launch vehicles from 130 for the earlier ICBM Atlas to 3 for the NASA Saturn. NASA made performance seem almost automatic!

As important as space exploration is, and will continue to be, in the final analysis the truly significant, long-range impact of the NASA program on civilization must be the realization that if a nation with adequate resources sets for itself a dramatic and ambitious, but realizable, goal and over time puts its money toward the accomplishment of that goal, it can pull it off. It is hoped that the example NASA has provided can be transformed and transfused into other societal-relevant, national goals. We here share a common interest in, and commitment to, the rehabilitation of the physically impaired. This national problem deteriorates the lives of many of our citizens and represents a vast economic disadvantage in terms of support costs and income.

Clearly, we must explore ways to make rehabilitation the focal point of a national "NASA-like" effort – a NASA-like approach in resources planning, getting on with the job, and producing results.

There were two very significant aspects to JFK's simple declarative statement a decade ago, which are terribly important in the human rehabilitation effort we have before us. First, JFK specified a well-defined mission, and NASA responded by designing a mission-oriented effort. The National Institutes of Health's role and contributions to basic medical science, through their support of fundamental research, is of inestimable value; but except for very infrequent examples such as the Visual Prosthesis Project in the National Institute of Neurological Diseases and Stroke, NIH very rarely defines missions. (The current Congressional-Administration debate on how to mount the "Cancer Crusade" is an example of the basic research-mission dichotomy.) We here and now want to define and effect a mission-oriented program in human rehabilitation!

Second, the JFK charge included a concise, objective measurement of accomplishment – an American on the moon. Chaplin (Chap. 9) and others have emphasized the need for objective measures of performance in rehabilitation. As we move into a massive, systematic, adequately supported, technologically based program in rehabilitation, we must bear in mind mission-orientation and objective measurement.

Norbert Wiener was the father and popularizer of the term *cybernetics*. His ill fortune in falling and breaking a hip put him into the Massachusetts General Hospital where he met Dr. Melvin J. Glimcher, then Chief of the Department of Orthopedic Surgery at MGH. Wiener's conviction that the human central nervous system was the appropriate source of control of a prosthetic augmentation to the human system initiated the interaction of the orthopedic surgeon and engineers, and led to the collaboration that produced the Boston Arm prosthesis. This device couples relevant bioelectric signals originating in the human brain to the control of an electromechanical elbow.

The Boston Arm prosthesis project at MIT illustrates some aspects of a national rehabilitation program. It is characteristic of the research, development, evaluation, and application process. The pitfalls and difficulties that we have experienced are endemic in similar attempts toward physical and sensory rehabilitation and must be overcome if we are to mount successfully a "NASA-like" program. A current benchmark on our Boston Arm is in the issue of *Newsweek* dated Sept. 6, 1971. As you open the front page, there on that glossy paper, in living color is an illustration of the Boston Arm on an amputee. It was nice to see that Liberty Mutual Insurance Company advertisement in a number of periodicals including a full page in the *Wall Street Journal.* Such exposure for a rehabilitation project and the insurance company's support and application which have made it possible is remarkable in our free-enterprise, profit-oriented economy.

In Chapter 2, Wyatt compares the cut-and-try attack on a problem versus NASA's in-depth approach. The university can ill afford the cut-and-try approach, but for somewhat different reasons. We can be goal-oriented just like NASA, but our central concern is for our students – our "material in process," so to speak. We want to turn out graduates who eschew cut-and-try work, and reach practical solutions systematically, bringing to bear all relevant scientific and other knowledge and techniques. The university thus represents a very fertile environment for the collaborative research and development that significant projects in rehabilitation must pursue.

The university environment greatly facilitates assembling appropriate talent. For example, a doctoral candidate researching an advanced prosthesis concept must have on his committee an MD familiar with orthopedics and rehabilitation.

The development of our Boston Arm began with the question, "What would be the ideal solution for a prosthesis to be fitted to an above-elbow amputee?" The obvious answer is an approach that best and most naturally employs the human's brain, spinal cord, peripheral nerves, and appropriate residual musculature to control the limb machine. The artificial device would derive control information from the human to modulate power to an actuator to drive the substitute limb. In turn, the artificial limb must generate sensory information to feed back to the human nervous system and brain. Thus, the man and machine become a synergistic unity: the man feeds efferent or motor control information to the machine, and the machine responds, delivering afferent or sensory information back to the man.

Any goal defines its relevant background knowledge. Thus, the thesis student (or his professor) tackling this problem had better acquire whatever information is pertinent, regardless of its disciplinary origin – anatomy, neurophysiology, muscle physiology, proprioceptive sensory feedback, etc.

Descriptive and quantitative models of the underlying systems play vital conceptualization and analyses roles. My MIT colleague, Professor Young, earlier asked Chaplin about the use of models of the neuromuscular system in the understanding of data generated by Dr. Chaplin's spastic muscle evaluator. Clearly, one must have one kind of model to best organize and evaluate data; other classes of models facilitate the design of devices that we ultimately wish to realize. Figure 13-1 shows a model of the neuromuscular-skeletal physiology relevant to the Boston Arm study.

To continue with our example, the doctoral student, after some period of preparation, is confronted with the obligation to define a specific hypothesis. This is an important point, because research in biomedical engineering sometimes fails to make explicit the hypothesis underlying a particular adventure.

For the Boston Arm, our hypothesis was: given upper-extremity amputation at a level that severed the muscle groups that prior to amputation controlled the anatomic elbow joint, was it feasible to detect electromyographic activity in the residual fragments of dysfunctional muscle and use this signal as input to a servomechanism that would operate an artificial elbow joint? If so, control of the prosthesis would be "natural," since the muscle fragments were presumably still coupled via peripheral nerves to the central nervous system, and therefore both controlled by, and providing sensory feedback to, the brain.

In an environment like MIT, as in NASA, one applies as sophisticated an approach as may prove useful in the elucidation of the feasibility of a concept. One doesn't helter-skelter build hardware to see whether the idea is reasonable; this would be a cut-and-try approach. Rather, computer simulation of the complex man-machine system is far more appropriate in the early stages of such an investigation.

The first doctoral thesis on the Boston Arm included computer simulation of potential ways of processing electromyographic data together with computer models of the dynamics and electromechanics of possible arm designs (Fig. 13-2). Normal or amputee subjects generated bioelectrical activity, which was detected with skin electrodes. After analog-digital conversion, these signals drove the "processor" and "hardware" models in the computer, which generated an oscilloscope display. The subject determined whether a particular limb "design," represented by certain computer models with specific parameter values, achieved a proper response.

Herein lies an important problem – the objective evaluation of a prosthesis and rehabilitation techniques in general. The ultimate measure of acceptance is the amputee saying, "This is great, it is just like my original arm." But it isn't satisfactory to operate with only that final criterion because of its inherent subjective nature. To proceed in an orderly and systematic fashion, it is necessary to define and apply quantitative means of assessing the project at each stage. For example, after the computer simulation "optimized" aspects of the design and before we built any hardware, we used tracking tasks to evaluate performance capability on a statistical basis. A variable representing the electromyographic activity the patient would have to generate were he to control an ultimate prosthesis adequately was presented dynamically. By continuously monitoring the bioelectricity the subject generated, and by calculating his tracking errors, we could numerically establish levels of performance, compare normals with amputees, compare among amputees with different surgical procedures, and so on.

These data provided the confidence to proceed into hardware. By this time, our man-interactive computer studies and the tracking task evaluation had defined the system shown in Figure 13-3. The processed electromyographic control signal generated by the amputee would compete with a negative feedback proportional to the load on the forearm. The choice of force feedback was deliberate; our presumption, consistent with the muscle physiology of Figure 13-1, but still to be tested, follows. When the amputee flexed a greater load or accelerated a given load more rapidly, the negative feedback would increase. The electromyographic signal he generated would have to be greater to overcome this feedback. The concommitant increase in contraction of his muscles would further excite the sensory organs in his muscle spindles and tendons, increasing the afferent feedback into the central nervous system, all in a "natural" fashion.

The transition from theory and software into design and hardware involves myriad decisions among as many alternatives (Fig. 13-4). These include forms of stored energy, kinds of power, specifications for force and speed, and the like. The maze of Figure 13-4 is characteristic of the manifold interlocking dimensions of the design problem, and of course all are subject to considerations of budget.

The design decisions are ultimately made, and another student proceeds to design hardware. Eureka! An amputee successfully controls the first physical limb, as in Figure 13-5. But design is an iterative process and after several stages of student and professional effort, quite respectable hardware evolves (Fig. 13-6). When routinely fitted, the amputee simply has to think about flexing his artificial limb, just as he thought about flexing his normal limb, and the prosthesis responds.

The design and use of psychophysical evaluation tasks to generate quantitative, objective data are an intrinsic part of any rehabilitation project, once biological-technological feasibility has been demonstrated.

What does this limb really do for the amputee? How is it superior to more traditional prosthetic approaches? One measure of performance is an assessment of a unilateral amputee performing a two-handed task using the EMG artificial elbow versus the traditional prosthesis (Fig. 13-7).

Our force feedback has been noted; we have also been concerned about position proprioception. You and I easily perform complex tasks because our joint, tendon, and muscle proprioceptors inform our brains of the dynamic state of all our joints all of the time. But an amputee loses this spatial cognizance, and may not know exactly where his artificial limb is. We have explored the feasibility of feeding back position information via a tactile presentation on the skin called the "phantom" display. Multiple, fixed-position stimulators can be modulated so as to generate the perception of a tactile sensation between the physical vibrators. In normal hearing, we identify the location of a noise source in space because of the different times of arrival of the sound to the two ears. A similar central nervous organization for the skin apparently provides for sensory summation in an analogous fashion.

With the use of two stimulators mounted on the socket of the elbow prosthesis, we have demonstrated that the amputee quickly learns to associate the position of the tactile phantom with elbow angle. Computer-controlled and -processed psychophysical testing has established the resolution, accuracy, information rate, and interactions of this sensory feedback approach. With this feedback, the amputee experiences a real improvement in his capacity to position the elbow without recourse to vision.

We can't stop with research! In the case in point, we have a demonstrably successful EMG elbow with a few models being worn routinely by amputees. Everybody likes it. But where does it go from there? This is a very, very tough and difficult question – biomedical engineering and market development.

NASA doesn't market a product, but it does make very refined, multiple copies of things. Well, in this rehabilitation area, we have to find ways of achieving refined, fully developed, production versions of our designs. We certainly wouldn't claim the Boston Arm is at that stage. We then have to create the means of producing multiple quantities of rehabilitation devices. We have to manage all the problems involved in market introduction. New delivery systems must be devised. Who will prescribe? Who will furnish? market? service? This is a very, very tough and difficult question – biomedical product engineering and market development.

It's great that we all get together and talk about the exciting studies we are undertaking. But we must remember that, right now, virtually no amputees, or paralytics, or sensory impaired humans benefit from this work. The blind man, woman, or child still uses Braille or a phonograph to "read" or a cane or a dog to be mobile. The "technology" is of the eighteenth or nineteenth century! The artificial limbs and braces routinely fitted to human beings are at the level of a "craft," "cottage," or "tinkering" technology. None of the hardware used in rehabilitation bears any resemblance to equipment commonplace in an Apollo mission. Were we visited by a Martian, he would be perplexed by the unbelievable gap between the technology of interplanetary satellites and of the primitive hardware applied to the blind, deaf, and maimed!

At MIT, we are extending the elbow to a multiple degree-of-freedom arm prosthesis. And we are working on a similar approach for the above knee amputee (Fig. 13-8). We hope to demonstrate that a knee prosthesis can be an adaptive joint that derives information from residual musculature controlled by the central nervous system. For example, if an amputee chose to change gait, the damping of the knee joint would respond appropriately and change the natural frequency of the mechanism. Or if the amputee chose to sit down, the knee would flex to an appropriate large angle, larger than the normal excursion in gait. Most above-knee amputees are geriatric. We hope that our approach can provide a natural "stumble control." For example, when the amputee anticipates falling, reflexive EMG signals would call for appropriate action at the knee joint so as to minimize hazard.

We are also interested in enhancing the mobility of the blind. This man-machine system includes a search device that probes the space in front of the blind traveler, processes the incoming information to identify obstacles, landmarks, and the like, and then presents information to the blind person through a substitute sensory modality. In Chapter 12, Pudenz mentioned our Pathsounder device, which uses ultrasound to probe and presents audio cues.

More recently we have been considering the phantom sensation used for the elbow angle display as a tactile output for the Pathsounder. A doctoral thesis completed in June demonstrates that two-dimensional information can be transmitted via this technique. For example, a mobility device could display on the abdomen the range and azimuth of obstacles confronting the blind traveler. Of course, the research, development, evaluation, and implementation of such a capability poses a catalog of problems similar to those we have been facing with the limb prosthesis.

It doesn't seem possible that there is any tougher problem than that of human mobility. We really know so exquisitely little about how we do get around. Consider a person leaving an auditorium. He works his way across several seated people, avoids their outstretched legs, misses three brief cases, catches two steps, finds the door. He knows where he is going and he will get there. But how did he do that? How did he ensure that every step would be a safe one, that there was someplace to stand, that he wouldn't embarrass or injure himself or someone else in the process? How did he maneuver – using visual, auditory, and tactual cues – through his complex space? How do you maneuver through a crowded cocktail party without awkward encounters? And beyond avoiding obstacles, how do we navigate? If we really intend to make the blind man mobile, we must solve not only the next step problem so to avoid the hazards of collision or embarrassment, but we have to understand the many problems encompassed in human navigation.

To get a handle on this question, we need a really complex, man-interactive computer simulation system, as in Figure 13-9, in which the human moves through a real space. The only instrument he has is a psychophysical display that tickles him, generates auditory cues, or produces some combination of these. The space must be real because in addition to the display cues he receives many other afferent cues, such as echoes and tactile information through his feet. As he makes his way through the space, a computer keeps track of him, models the search, detection, and processing capability of a tentative mobility device, and telemeters the cue information to the psychophysical display for presentation to the traveler.

One of the great strengths of man-interactive computer simulation techniques, as in our arm or leg problems and this mobility approach, is the capacity of the computer to keep "book" on performance. It provides the data base for objective measure of the efficacy of any particular system.

The dimensions of human rehabilitation needs are awesome: the statistics tell us that 12 percent of Americans are physically impaired in one way or another. The benefits of effective rehabilitation are considerable; one measure is that a dollar committed to rehabilitation averages into a $35 return. Travelers Insurance Co. estimated that the lifetime cost of support and income loss of a particular subset of 67,000 blinded Americans discounted at 5 percent is $4.02 billion. Just as JFK set the Moon as a national goal a decade ago, now, for both economic and humane reasons, we must establish a similar mission to apply technology to those who suffer physical impairment.

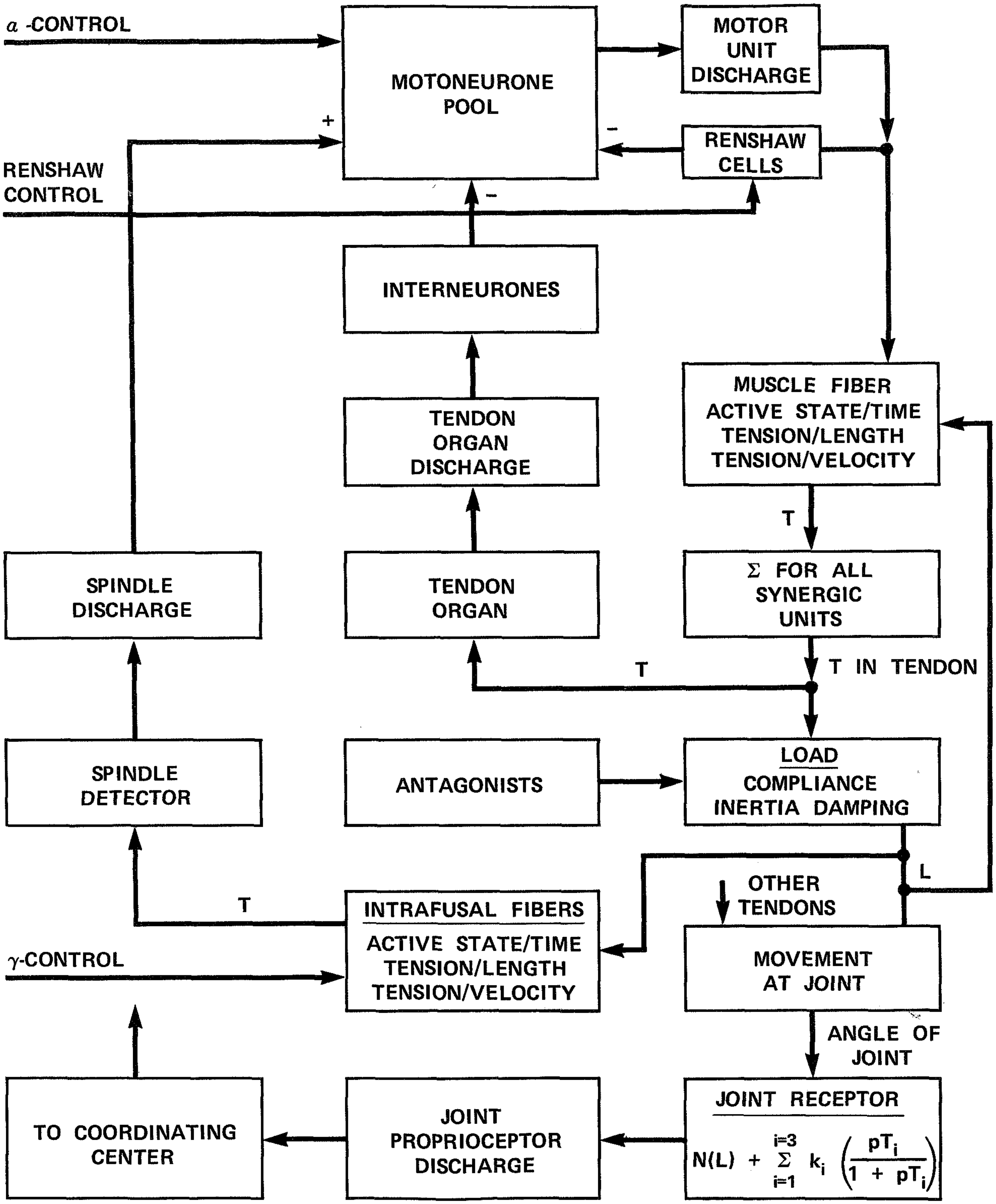

Fig. 13-1.— Neuromuscular-skeletal physiology relevant to the Boston Arm study, from T. D. M. Roberts, *The Neurophysiology of the Postural Mechanisms*, Plenum Press, 1967.

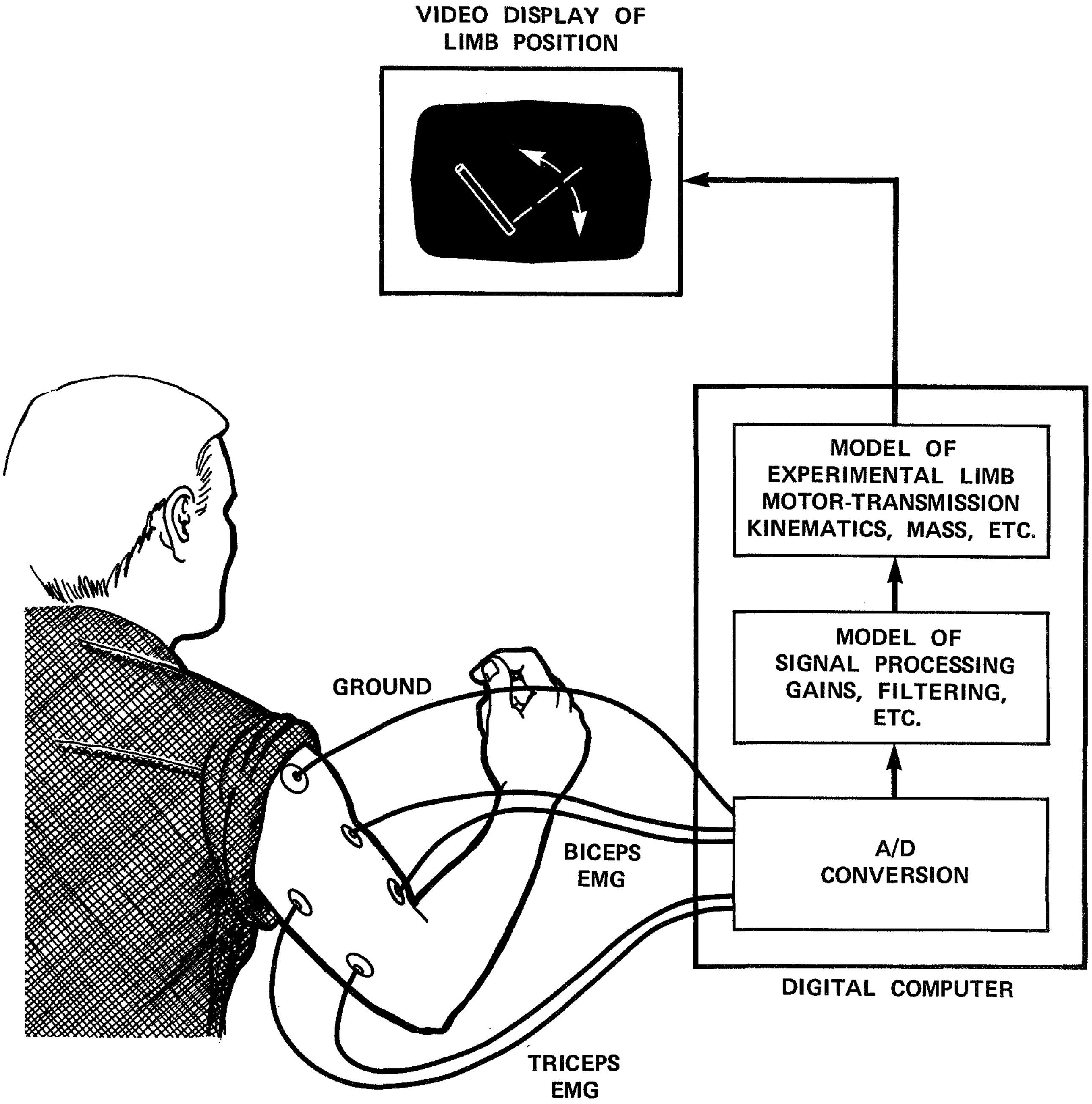

Fig. 13-2.– Main-interactive, real-time, computer simulation of the Boston Arm.

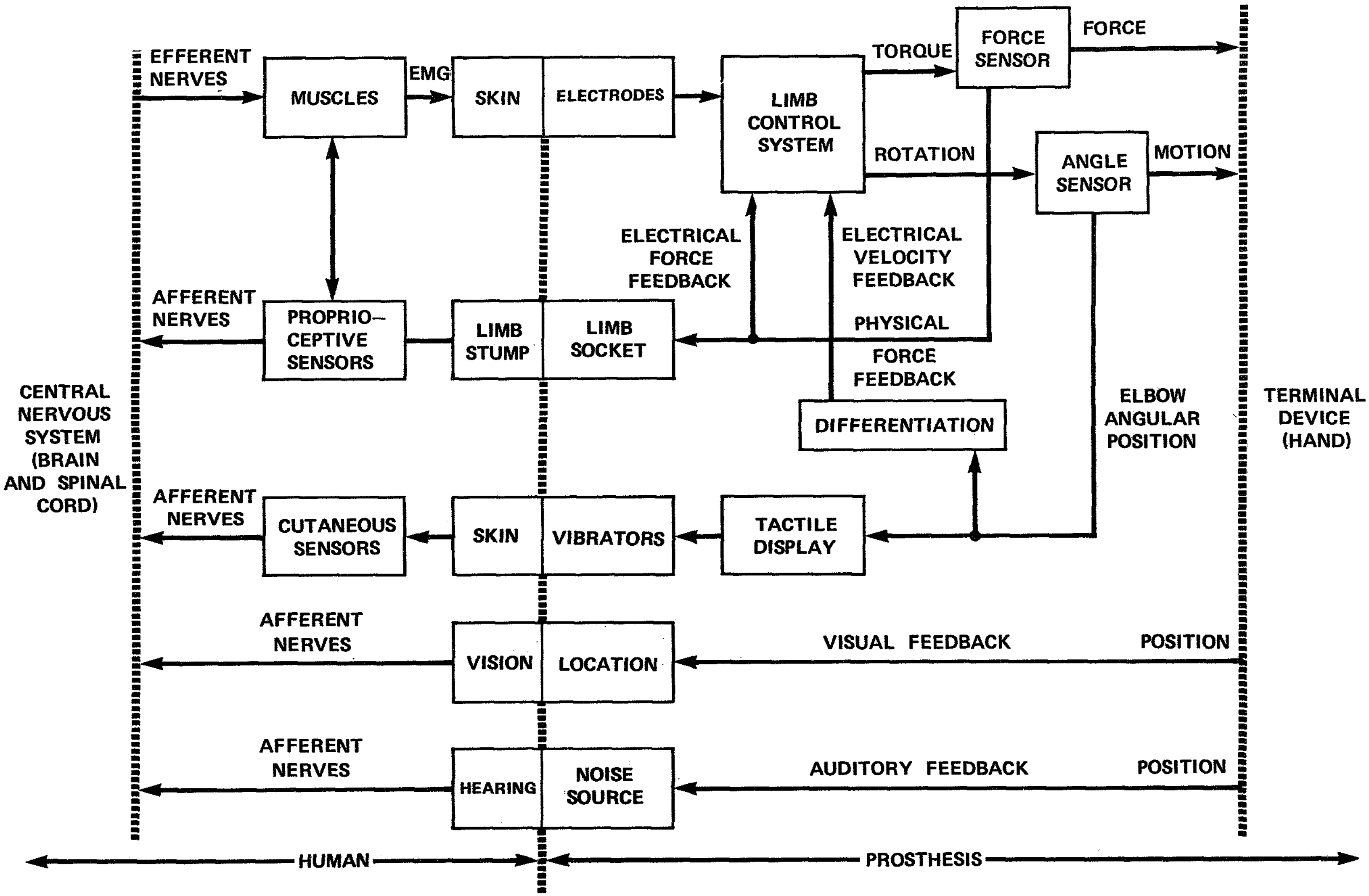

Fig. 13-3.– The physiologic-mechanistic symbiosis of the Boston Arm.

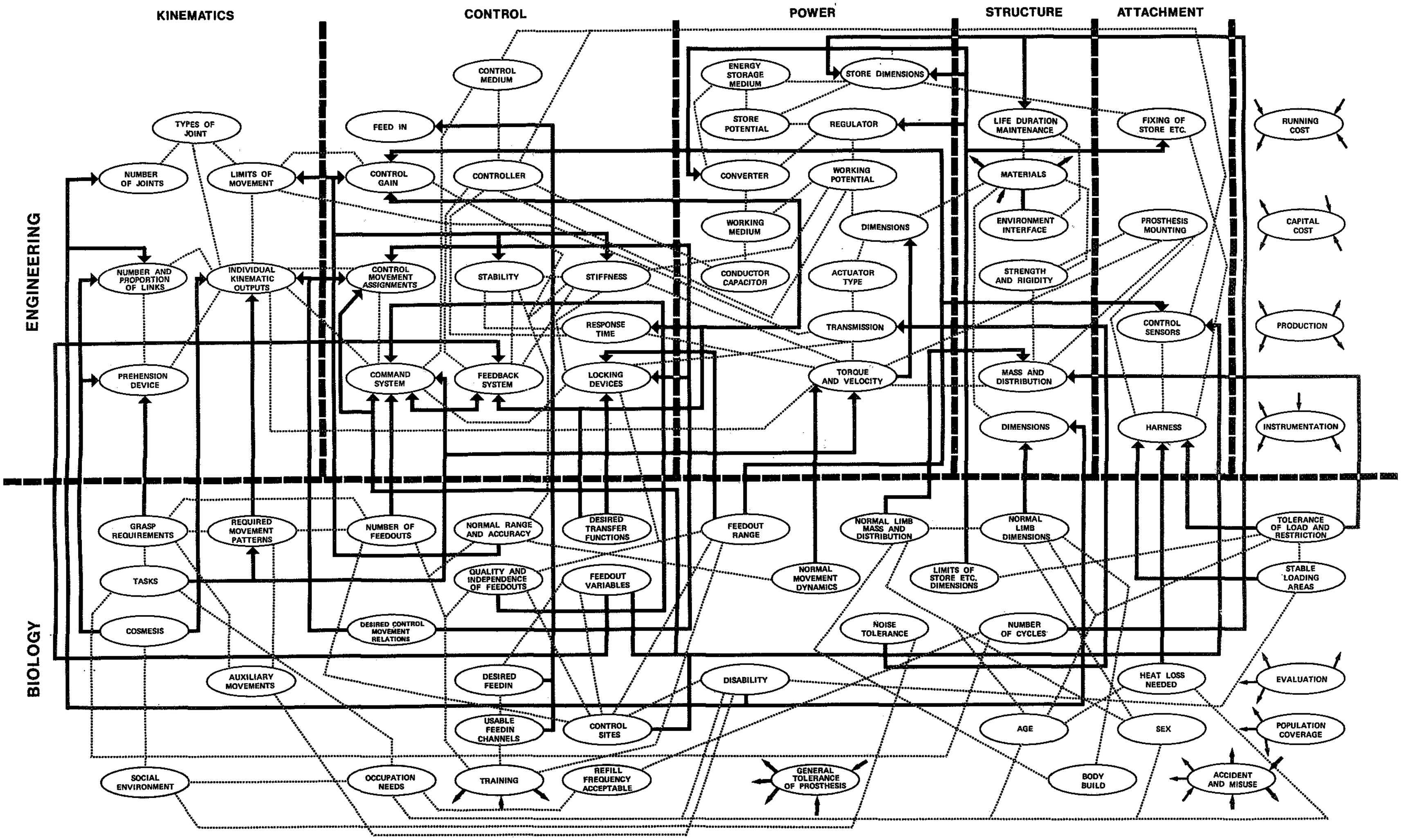

Fig. 13-4.– Prosthesis design map showing biological factors influencing aspects of the engineering system, from S. R. Montgomery, *The Basic Problems of Prehension Movement and Control of Artificial Limbs*, The Institute of Mechanical Engineer, London, 1969, p. 68.

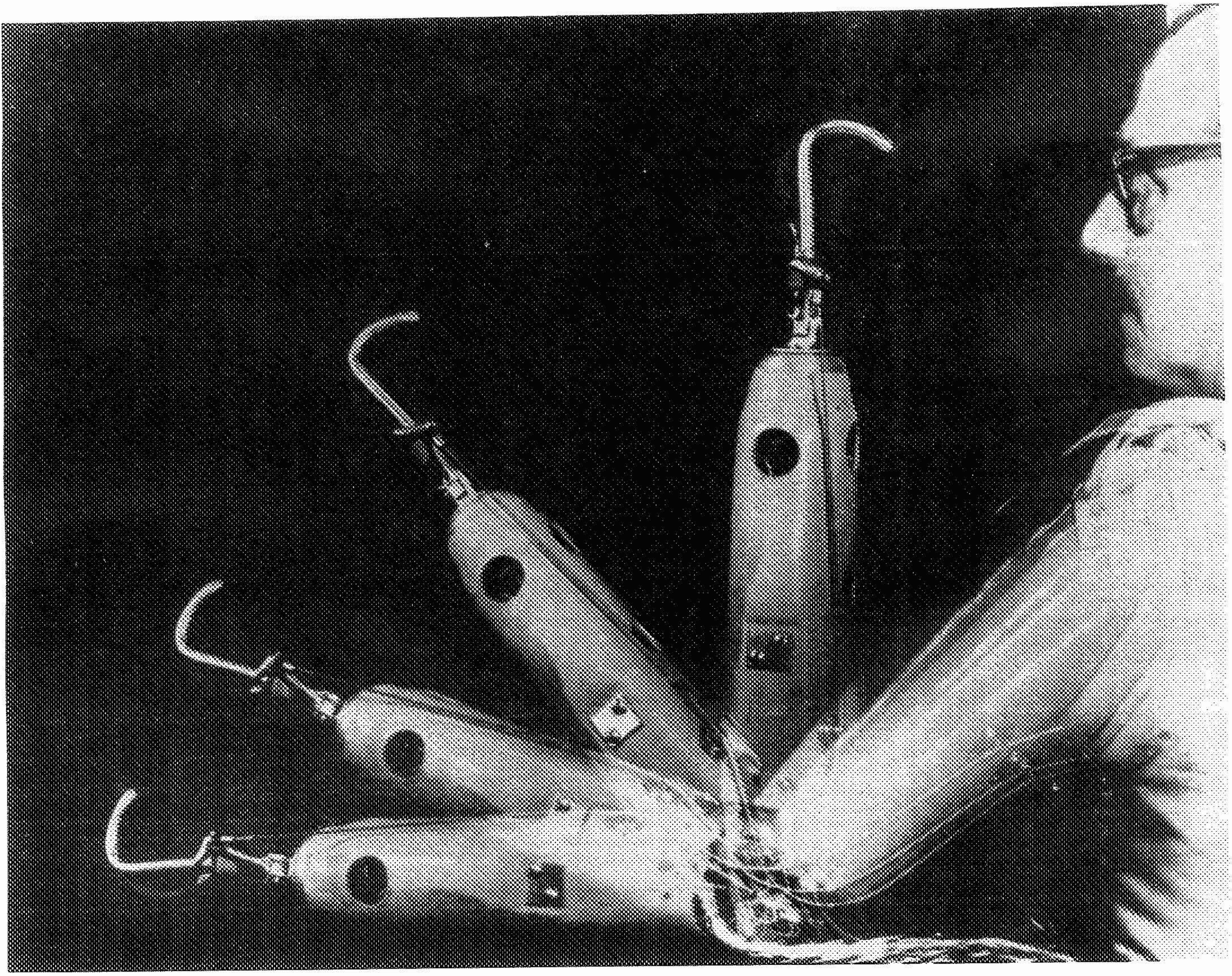

Fig. 13-5.– The first wearable Boston Arm (with acknowledgement to the Liberty Mutual Insurance Company, Boston, Massachusetts).

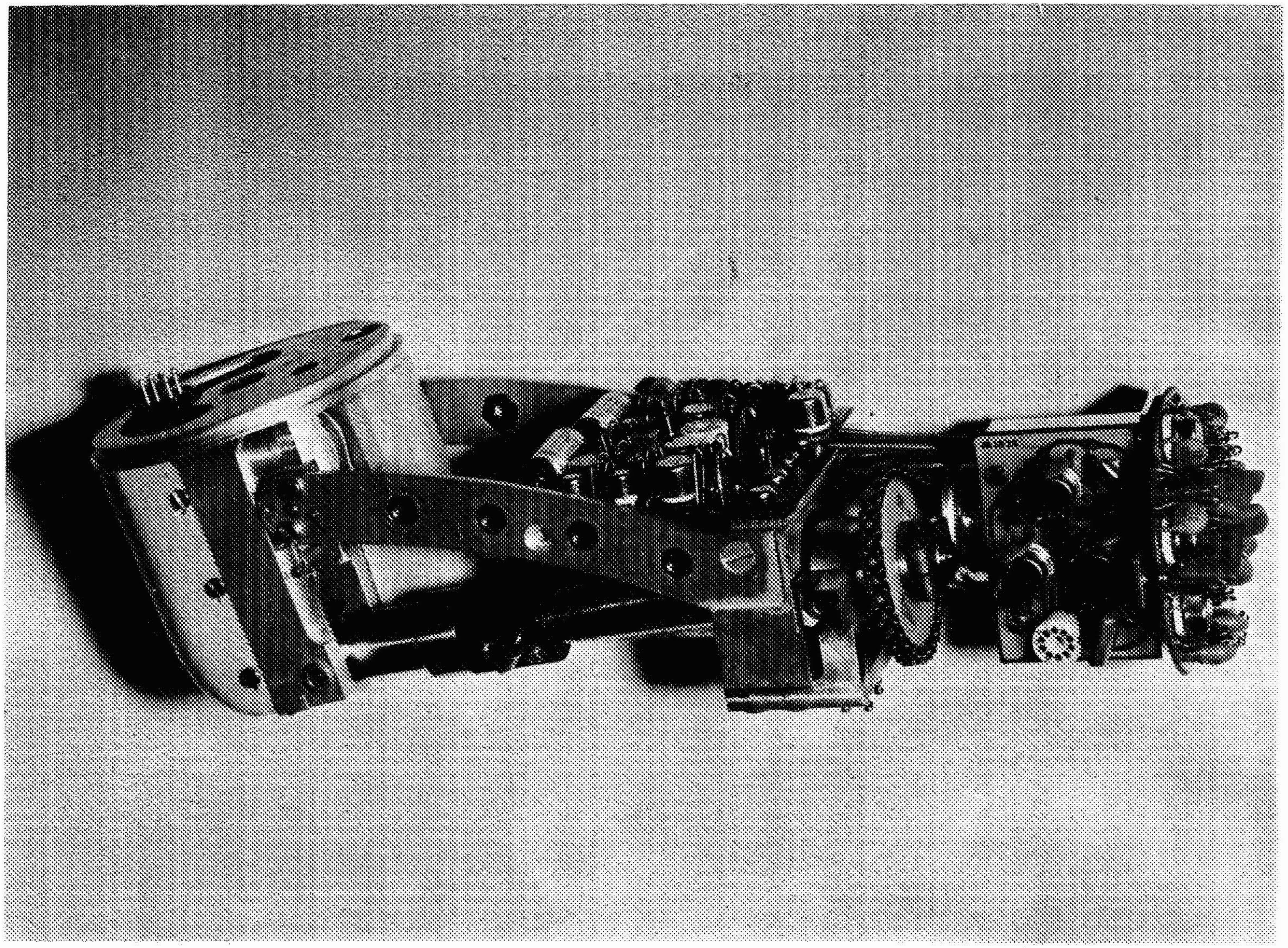

Fig. 13-6.– The elbow and forearm of the Boston Arm, illustrating electronic and electro-mechanical components (with acknowledgement to the Liberty Mutual Insurance Company, Boston, Massachusetts).

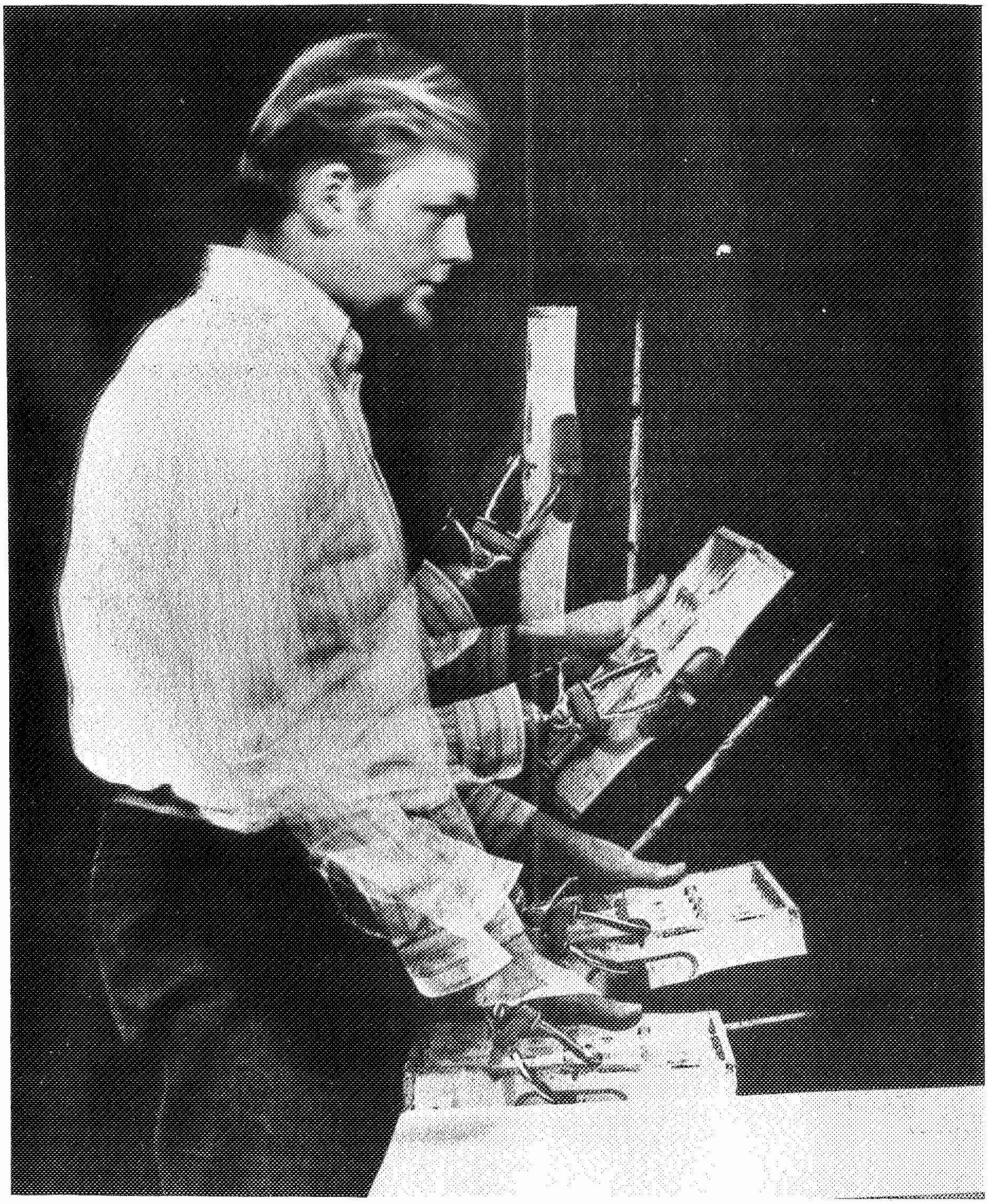

Fig. 13-7.– A unilateral above-elbow amputee performs two-handed tasks with natural synergy of both elbows (with acknowledgement to the Liberty Mutual Insurance Company, Boston, Massachusetts).

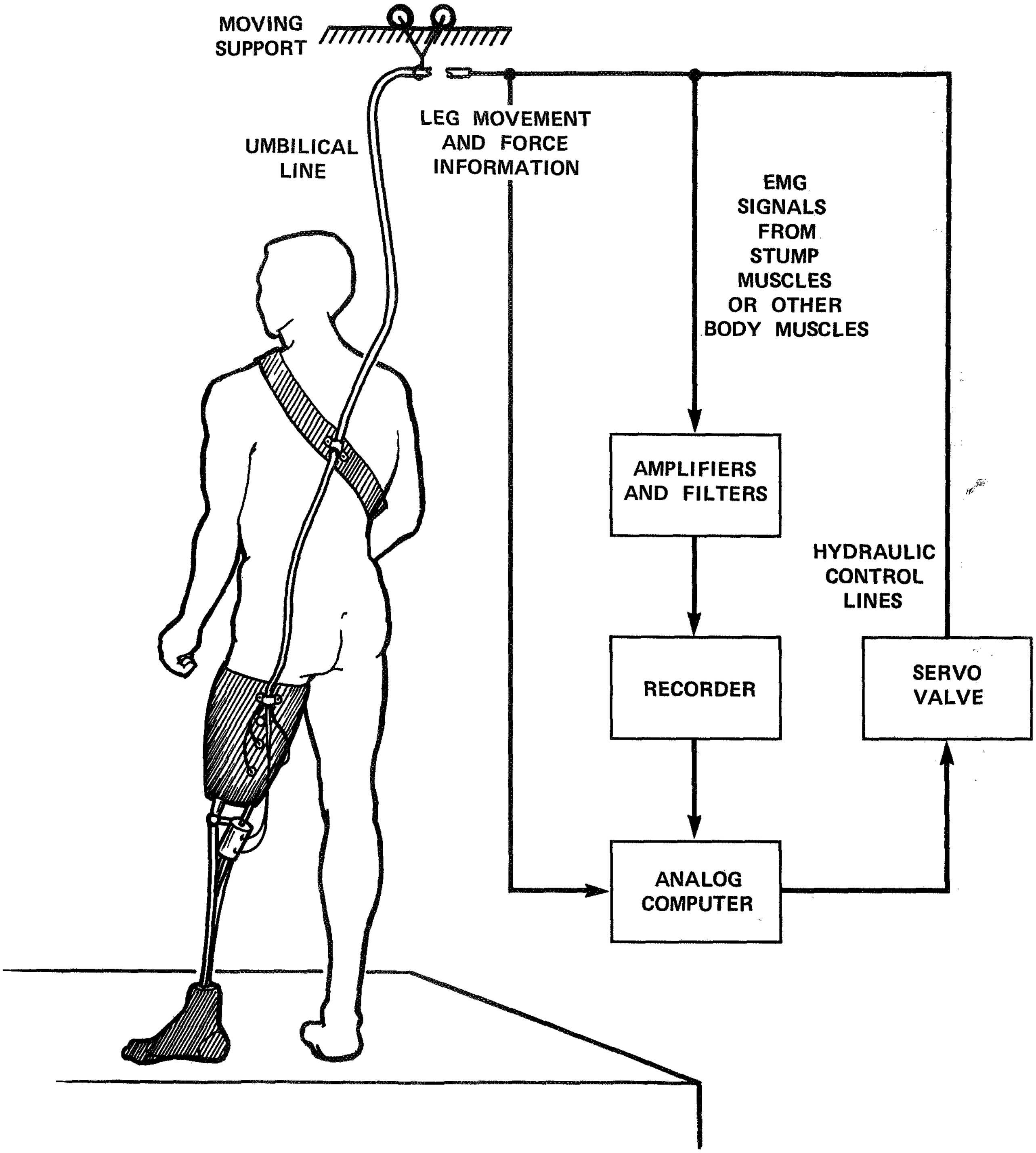

Fig. 13-8.– The MIT man-interactive computer simulation facility for study of EMG-controlled above-knee prostheses.

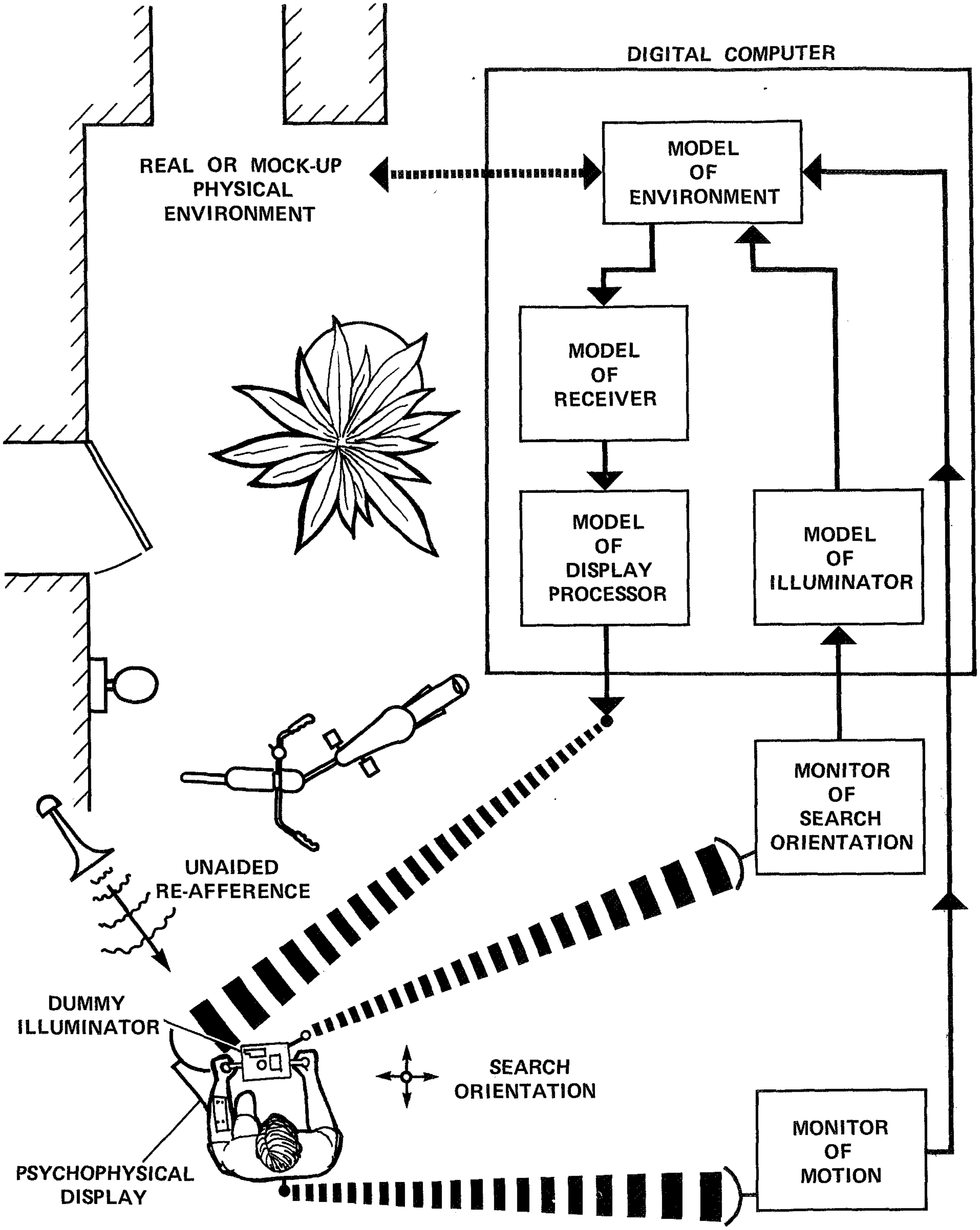

Fig. 13-9.– The proposed man-interactive computer simulation system to study human mobility and develop orientation, travel and navigation aids for the visually impaired.

Chapter 14

THE CURRENT STATUS OF REHABILITATION ENGINEERING

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Much of the preceding material deals with the current status of rehabilitation engineering. Here we add a few more pieces to the total picture and touch on some of the philosophical implications of our field. Both mechanical and electrical engineering devices are discussed.

For a time, the term *myocybernetics* was used in referring to the science of communication and control in neuromusculoskeletal systems. It seemed a logical subclassification of Wiener's original concepts as outlined by Mann in Chapter 13. The more general term, *rehabilitation engineering*, is catching on, however, and throughout the country, this concept is being applied with greater frequency to the activities we are talking about.

EARLY DEVICES

One patent dated 1854 is a nice example of a mechanical engineering approach to a medical problem. According to the inventor, a trap is baited, attached to a string, and swallowed by the patient after a fast of suitable duration to make the worm hungry. It is a tapeworm trap, you see. The worm seizes the bait and his head is caught in the trap, which is then withdrawn from the patient's stomach by the string, which has been hanging from the mouth, dragging after it the whole length of the worm.

In 1898, one of the first uses of electrical stimulation was proposed, and one fellow invented a useful improvement in the electroextraction of poisons from the human body. Basically, he used positive and negative plates, and ran a current in the correct direction from the neck to the feet, the poisons then being washed out of the body into the proper receiver at the feet: "For vegetable poisons, I employ a vegetable receiver instead of a mineral or copper one. And for animal poisons, I use an animal receiver such as raw meat. The device [thus is] capable of use with the mineral, vegetable, or general receivers without further change than to equip it with the kind of receiver applicable."

SOME RECENT DEVELOPMENTS

Waterbeds for the Prevention of Decubitus Ulcers

We now consider some particular recent developments that are representative of medical engineering systems. These include means of preventing bedsores, mobility aids, upper extremity orthoses, and electrical stimulation.

The first has to do with a problem of the decubitus ulcer, or the bedsore. Just recently, the first patient has been placed on a new bed (Fig. 14-1) that shows considerable promise of preventing the developments of bedsores and may prove to be a therapeutic bed for healing such sores.

The idea is very simple and has appealed to people for many, many years. The body is floated on a fluid, supported by the hydrostatic pressure, and a maximum pressure of about 25 mm Hg is thereby achieved in the case of the human body floating in water. This pressure is well below the peripheral circulation pressure in normal skin and therefore is safe over extended periods of time. (The ordinary water bed sold in the stores won't work at all, because you are really sleeping on the cover and not on the water.) The trouble with some of the hospital type water beds is that the body sinks down into the water, because its specific gravity is similar to that of water, and stability cannot be achieved. A good example is the position of a person floating in a swimming pool – his feet and legs immediately begin to sink. There have been some attempts to build such beds in Boston, and they work as far as the pressure is concerned but they are unsatisfactory from the standpoint of patient management, nursing, and comfort.

We proposed that the patient float on a fluid of specific gravity 2 instead of water. Suddenly, the situation is stable, each limb of the body is supported by the hydrostatic pressure. It turns out the maximum pressure on the patient is exactly the same as if he were in water, because although the fluid density is twice that of water, the depth he goes in is only half as much.

A really serious decubitus ulcer is extremely difficult and extremely expensive to deal with. The first version of our bed was a tub with some heaters in it and filled with oil well drilling mud. In searching for a proper fluid of specific gravity 2, we discovered that it was not easy to find. The technology utilization activity of NASA provided the hint. Through a T.U. Bulletin, provided by our local officer in Los Angeles, we learned about a development in connection with a nosecone tester here at Ames, by which iron pyrites were ground fine into a stabilized colloidal suspension, thereby achieving the specific gravity of 3 or 4. The nosecone was put into the suspension and the pressure profile of the reentry vehicle was simulated in that fashion. This gave us the idea, then, of using oil well drilling mud. Actually, the material in the bed here is barium sulphate, or barite, ground very, very fine. It is the same thing we give a patient having an upper GI series of X-rays. It is perfectly benign to the human body, and seems an all-around good solution to the problem. Bartonites are added to assist the suspension.

We put an air mattress on top of the bed to provide a reasonably firm surface when needed for changing the patient's clothes, or managing the patient, rather than having him down into the bed. The second models have worked out pretty well.

We have had a quadriplegic patient in the bed now for several weeks (Fig. 14-1); he has not been turned at night. During the first few weeks we checked him very carefully, and he has developed no reddened areas. He has a complicated brace around his neck to hold his head straight. That brace just goes down into the mud – it doesn't bother him at all. A bed sore in the middle of his back from a previous hospital experience is getting better. He now sleeps through the night without drugs, whereas before he was turned every two hours with drugs. We are very excited about the potential implications of this particular device.

Mobility Aids

A wide variety of electric wheelchairs have been developed at Rancho Los Amigos Hospital and elsewhere. One of these is controlled by a tongue switch located on the patient's chest. The switch controls speeds forward, backward, and so on. Another method of control, if there are trace movements of the hand, is a stick on the unit on the side of the wheelchair. One means is a pressure-sensitive plate in an XY set of coordinates.

The original sight-controlled wheelchair was developed by NASA and is being evaluated in a number of institutions including Rancho. We also are interested in the sight control concept and have a similar project under way that is based on a somewhat different principle but is virtually the same. This project uses an eyeglass control system in which a light source is beamed on the pupil, is reflected back into receptors, and provides a number of degrees of freedom of movement.

Upper Extremity Orthoses

Many paralyzed patients have the possibility of moving their arms if gravity can be overcome. One device developed for this purpose is a so-called "mobile arm support," which permits a good deal of function, controlled by the patient, with the simplest kind of passive devices, and no external power or sophisticated controls. In this area, we must resist the temptation to try to design complicated systems for patients who can get away with something as simple as this. More complicated is an electrically driven hand splint, which enables this patient to open and close his hand, although his arms are still supported by gravity mobile arm supports.

A more sophisticated device is an externally powered arm. The Rancho electric arm was discussed by Hsu (Chap. 8). It is controlled by on-off tongue switches. The motors come to speed and stop as the tongue switches are activated. A newer version under evaluation uses a proportional control system, which sets the pressure on the tongue switch and controls the speed of the motor around the joint. With this system, patients have been able to achieve quite remarkable performances, for example stacking up blocks with this same degree of skill with which you or I could do it.

Electrical Stimulation

Peroneal Nerve.– Hsu discusses the peroneal brace stimulation in Chapter 8. The idea is to overcome drop-foot in the case of stroke by electrically stimulating the peroneal nerve. (See Fig. 14-2.) Equipment being developed jointly by the Medtronic Corporation and Ranch Los Amigos consists of a passive type receiver surgically implanted in the thigh, and an electrode wire with two platinum electrodes that are wrapped around the peroneal nerve. A plastic device is used to tunnel under the skin from the thigh down to the nerve, and fabric is used to suture the system in place so that it won't move around. We are evaluating a system that uses a radio link from the heel to the thigh so there is no wire. There is still a wire to the antenna, which is held in place over the passive receiver by tape.

A major advantage of the implant system is that the particular correction you would achieve sometimes depends on which branches of the peroneal nerve are actually excited. It is not quite sufficient in many cases to just stimulate the whole nerve. So the surgeon separates out the various branches, and by actually stimulating the patient on the operating table, he can determine whether the foot dorsiflexes in a way that he chooses, and make sure he is in the right place and has the right group of nerves. Then he can go ahead and put the implant in place.

Gluteus and Quadriceps Muscles. Stimulators were implanted in the gluteus (hips) and quadriceps (legs) muscles of a patient who is a paraplegic from the hip on down – a fully paralyzed person who cannot ever be expected to walk. Two things happened with this patient that were fairly interesting. First, she was able to get up and step around a bit. We would never say she could walk: in terms of achieving a walking capability through this stimulator, it is certainly not a success. In terms of the hypertrophy of her muscles, however, it was a remarkable success. In the beginning, when her quadriceps were stimulated, her leg would barely move from the floor. Under stimulation, she now can hold her leg out in front of her for over half an hour – something you and I perhaps could do under hypnosis, but certainly we would have difficulty doing it voluntarily. This ability is achieved through cyclic stimulation during the night, by a device that stimulates the muscle for 20 seconds and is turned off for 30 seconds. We need to find out exactly what is happening from a fatigue point of view – why the muscle doesn't fatigue under electrical stimulation, when we know that in most cases a skeletal muscle electrically stimulated tends to fatigue very rapidly during stimulation. It is a very real possibility – and a vital objective of research – that such systems further refined and controlled by simplified patterned computers, will enable such patients to walk.

Other Developments. An experimental electrode has been developed that consists of a carbon button designed for percutaneous transmission. With this device, there has been no infection, no tendency to break loose, and so forth. Another, somewhat crude, electrode has two wires and a third wire attached to the carbon button itself. The electrical impedance between the implanted carbon and the skin is lower than almost any other kind of electrical connection to the surface of the skin. With such a device, attached to a human nerve, we will then have a "window" to that nerve. We can find out precisely what the waveforms are on the nerve during electrical stimulation. For example, we know that you can have an implant stimulator that produces either constant current or constant voltage pulses, but if you know they are constant current, you don't really know the waveform of the voltage – that is, the impedance between the electrodes and the nerve. To date, there has been no way to measure it except through an acute experiment where the nerves are exposed. So this device will provide such measurements as well as a means of experimenting with nerve blocking and with electrical stimulation, and perhaps studying the control of spasticity, and so on.

THE DESIGN, DEVELOPMENT, AND PRODUCTION PROCESS

The design, development, and production process in rehabilitation engineering differs in many ways from the process whereby, for example, a contractor develops a technological device for NASA. In some ways, it may be more difficult. The engineer's approach to a project design typically begins with a sketch of the various goals and activities anticipated. Such diagrams change through the years and differ among people, but by and large they always turn out to have basically the same elements and the same concepts. It is a feedback or iterative process. The process starts with research and development, which may be initiated by pure scientific curiosity; but in rehabilitation engineering, it is more appropriate for research and development to be initiated by goals set by some goal setting and planning function. This is perhaps a way of saying that it should be "mission-oriented," as Mann noted in Chapter 13, and that actual performance goals should be set up all along the line.

To illustrate the design, development, and production process in a general way, let's start with a customer. Who is the customer? It is not the U.S. Government, it is not a federal agency, it is not the consumer on the street. It is a very different customer – probably a physician in a clinic or in private practice. These devices are prescribed by physicians, and while they may not always be sold directly to the physician, he certainly makes the decision as to whether the device will be sold. Because the physician takes full responsibility for everything he does in his special relationship to the patient, the device he prescribes must have an extremely high degree of reliability. It has got to work! It cannot fail!

The physician must understand what the device is for, what the indications and contraindications are, and he has to be able to educate his team in the application of the device. These problems of education, training, and distribution lend a uniqueness to the product of rehabilitation engineering as compared with many other devices.

In the development of many technical devices for aerospace or other uses, it is possible to sit down in the beginning and write a set of technical specifications, vibration characteristics, frequency characteristics, strength characteristics, a performance specification, and so on. When the device has been built, it is tested against these specifications and either measures up to them or doesn't. If it does, the device is accepted, and that is that. The whole project is a success. But it is extremely difficult in dealing with patients in a clinical environment for anybody to set the initial specifications for what a device has to do. This is because all aspects of a patient's problem are not recognized initially. Not until you actually try to make and test the device in a clinical environment does the medical and engineering team begin to understand the problem fully. Thus, the device goes back to redesign and is improved through changes in design specifications. In other words, the people who set the original goals have to change their concepts a little bit and the designers have to do a better job. And it goes back again into some sort of internal evaluation. This process amounts to evaluation/redesign loop, and in medical engineering devices, you go round and round this loop more often than in almost any other kind of engineering devices. It costs more money, and it takes more resources. The frustrations and the expectations are very difficult to reconcile. But eventually a device reaches the point where somebody can make a decision that it should go into at least limited product development.

The problems of maintenance and repair and the problems of clinical evaluation I think are obvious to all of us. Mechanical and electromechanical devices never get better. The surgeon repairs a human body and does a halfway job; the body takes over, and finishes the job, and gets better. The mechanical device in a human body can only get worse, and sooner or later, it is going to have to be checked, repaired, and maintained. So any company that wants to produce these devices must have a means of ensuring that they are kept in working condition.

So these are some of the issues that face rehabilitation engineering in making actual devices available to a wide variety of people. If the goal of rehabilitation engineering – to improve the quality of life of disabled people through the application of technology – is to be achieved, it has to go through something like this sort of process.

DISCUSSION

Q. With regard to the decubitus ulcers and the very extensive burns, we have found a phenomenal success in treating these in a hyperbaric chamber with localized oxygen, enclosed for almost days.

On the graphite buttons, how firmly are they held, how long does it take for them to become firm, and once the skin takes to them, how firmly are they held? Can you slide a cap over it mechanically?

A. Well, I can only speak about my own personal experiences. I have had such buttons in my arm. And they were fairly firm. I knocked one of them out of my arm with a strong mechanical impact which tore the tissue and produced bleeding and so on. So that it was reasonably firmly implanted. The type that is going around with the wheel-like spokes sticking in it seems to be quite successful. First, it is made of pyrolytic carbon, which is a porous form of carbon and biologically very compatible with tissue, as compared with the shiny vitreous carbon some of us are familiar with. Second, the tissue develops around those spokes. And all I can say is that we have had them in the thigh and arms of some patients for over two and a half to three months. These patients were subjected to normal nursing care and the devices stayed in very well.

Q. Are you going to fasten the wire into the button before you implant it, or are you going to make contact with it afterward?

A. The wire is biologically sealed through the button to its final connector.

Q. In other words, it is through the skin to begin with? A. Yes.

Q. If you leave the patients for long periods on the water bed, do you have any problems with their developing pneumonia?

A. Yes. The bed certainly has the capability of not requiring the patient to be turned because of pressure of sores. But there are a lot of reasons for turning patients, to prevent blood pooling, to control respiratory distress, to prevent contractures, psychological reasons and so on. Normally, these patients are up and about during the day, and all I am really talking about is from 10:00 o'clock at night until 7:00 o'clock in the morning. Your question is a good one. In fact, that is a problem with the bed, because when the nurses are freed from having to turn the patient, they suddenly forget that there are these other issues, too, that must be attended to. And so it means that a whole new discipline has to be developed.

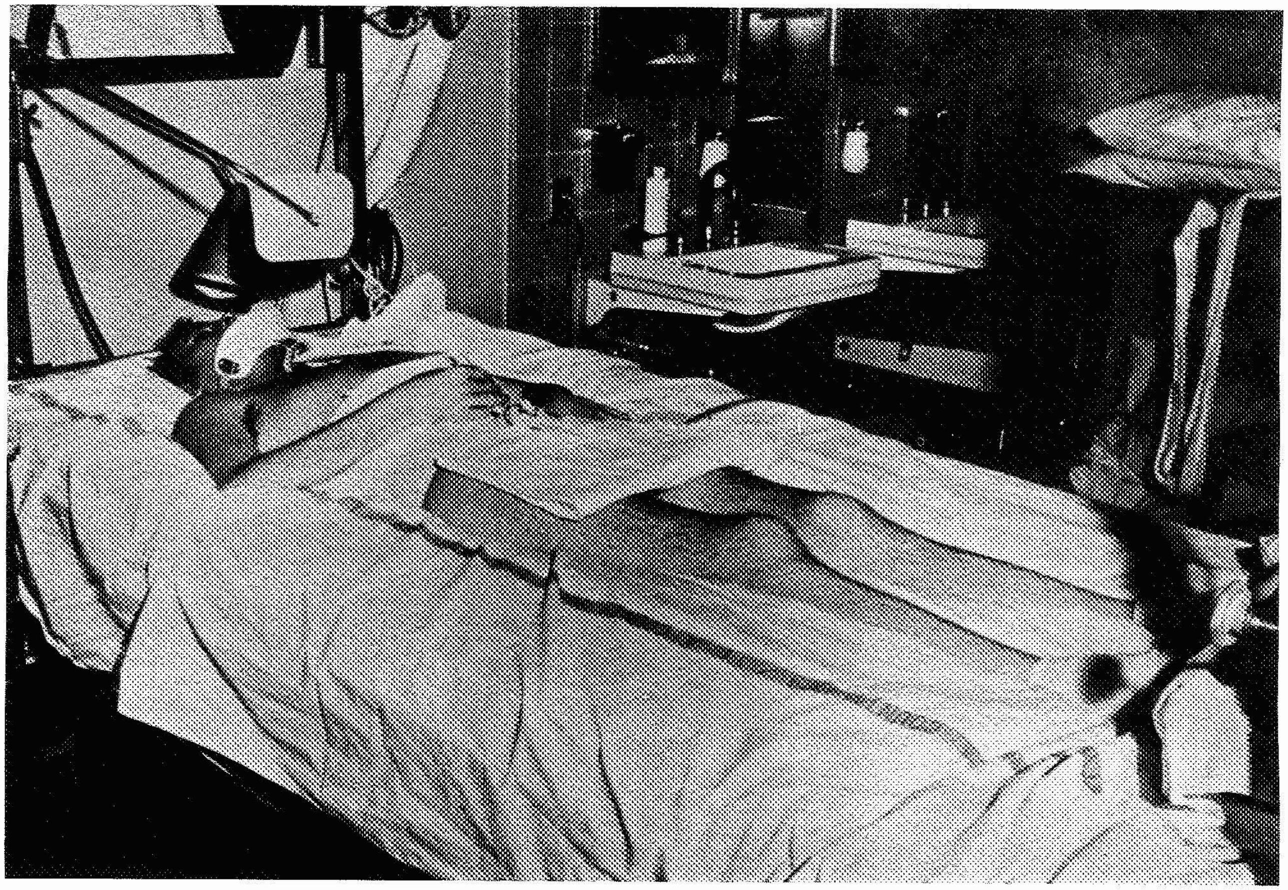

Fig. 14-1.– Quadriplegic patient in Rancho Flotation Bed.

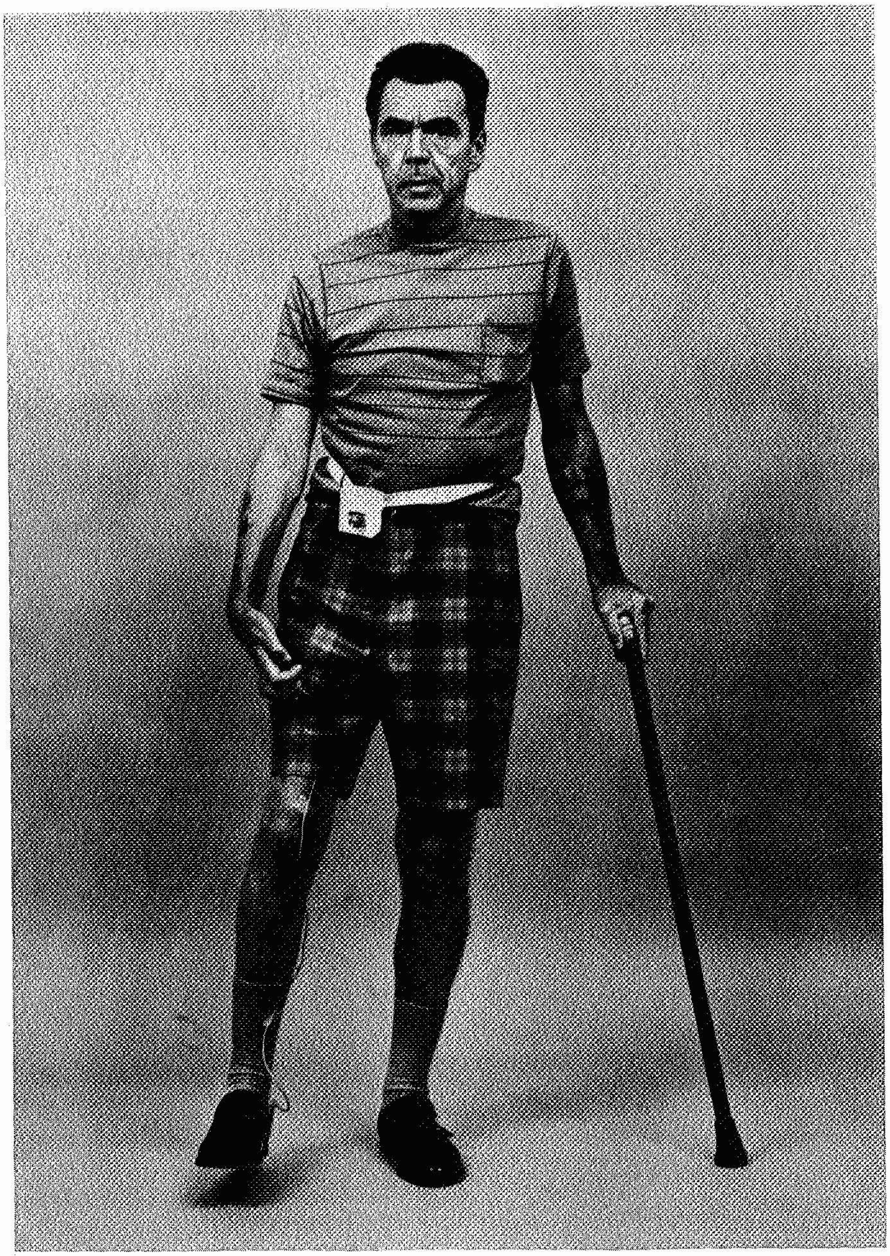

Fig. 14-2.– Stroke patient equipped with Rancho Los Amigos Hospital – Medtronic, Inc., peroneal nerve stimulator.

Chapter 15

EXOSKELETAL TECHNOLOGY

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This chapter is devoted primarily to a discussion of the possible applications of exoskeletal technology developed at Ames recently in our spacesuit effort and currently in our teleoperator program.

THE EXOSKELETAL SPACESUIT

About seven years ago, the Biotechnology Division of Life Sciences at Ames initiated programs to develop new concepts for spacesuits and life support systems.

A man operating out in space or on an extraterrestrial body for long periods of time must be provided with support systems having high and predictable reliability. With this in mind, we decided to try to develop an exoskeletal spacesuit – a spacesuit utilizing strictly rigid materials, which are inherently more reliable than soft fabrics.

We first developed what has come to be known as the "stovepipe joint" (Fig. 15-1). We fabricated the upper torso of a suit, attached it to the top of a cylinder, and pressurized it to 5 psi. We tested this device to determine the feasibility of the concept and whether we could get a complete range of motion with it. From our evaluation, we were quite confident that we could build an entire suit based on the joint concept. We then fabricated the lower torso and attached it to the system on top of the cylinder. Although the suit is fabricated of fiberglass, a rigid material, soft material can be attached between the bearings and races for stowage, and when the suit is pressurized, the softer material essentially becomes rigid as well. The completed suit (Fig. 15-2), called the Ames AX-I (Ames Experimental Model I Spacesuit), can be pressurized to 1 atm (14.7 psi).

After design refinements a second prototype was developed – the AX-II (Fig. 15-3). One improvement was a reduction in shoulder width, so that it was compatible with the current width requirements in the crew station of the vehicle. To achieve additional upper torso mobility, we placed a bearing at about 30 deg angle with the spinal axis, which yielded a little more forward motion in the stainless steel waist joint. Again, the design pressure was approximately 5 psi. We have demonstrated that we can achieve a full range of motion with this exoskeletal technology. We also have mockups with various differences in the bearing orientation and ranges of motion.

This technology has been developed over the past seven years, and the suit itself was completed approximately two years ago. We have been exploring other possible applications of the basic concepts that were developed in the suit project effort. One possibility, in which there is considerable interest at Ames, is the extension of man's capability in space by teleoperator systems – master-slave systems. There may be missions where a teleoperator and an astronaut together can make a more efficient working team. So, having an exoskeletal suit that is truly anthropomorphic, we asked, why not power it, and use it as a teleoperator?

In the master-slave teleoperator system, you have a master, which provides a control signal through electronics to "move" the slave. The slave, which is powered by some means, can be electronically controlled by a man in an arm. In one case, the slave is powered by dc motors with harmonic drives. Another mode is possible in which the system is controlled through a computer, preprogrammed to perform maintenance or other desired tasks. In this mode, it is more like a robot.

In the current design of the system (Fig. 15-4), the master would be essentially the same arm as on the suit, except that instead of having seals in the bearings, we now have a potentiometer element. The bearing housings are essentially a pot, and the man's arm is right inside the potentiometer. The dc motor harmonic drives move the slave arm so that the position of the slave is identical to that of the master. The slave arm is powered with motors internal to the structure, but they could be external to the structure, leaving the center of the cylinder free for a human arm. If we can make a slave arm do what a human arm can do, there is no reason why the slave arm itself cannot, in reverse, power a human arm.

We essentially will have a master-slave system. At the moment it is more of a research tool than a piece of operational hardware. The operator has his master on his arm, and a 3D TV system provides a visual check on the task that the slave is performing. After a certain amount of training, the slave motions are turned over to some central control system or computer housed on the outside. In this system, we have force feedback to the operator, hopefully also tactile feedback and a visual scene.

APPLICATIONS FOR THE NEUROLOGICALLY HANDICAPPED

In many neurological disorders, including certain types of cerebral palsy, the arm motions are erratic. When the patient is asked to touch his mouth, we may see rather large amplitudes and divergent motions any time he tries to position his arm to achieve that simple action. It may be very difficult for him even to feed himself.

For such a patient, it might be possible to apply our exoskeletal technology as a therapeutic aid, orthotic device, or a physical therapy aid. We visualize the exoskeletal structure on the patient, certainly not enclosed as in the suit, to provide some sort of mechanical damping for irregular motions (Fig. 15-5). We might propose that in the bearing housings, instead of seals, we provide a mechanism comprising a flexible tube with fluid in it, rollers, and an orifice, such that with any sort of motions of the conical segments, the roller must pump fluid through the orifice. We now have a velocity-sensitive system that would provide a resistance proportional to the velocity, and thus reduce the amplitude of motion of the arm so that he could at least become self-sufficient in feeding and possibly other operations.

Another possibility is a myoprosthesis (Fig. 15-6) – a powered arm by which an individual who has lost the use of his muscles now controls his arm through perhaps, a sight switch (as discussed by Reswick, Chap. 14) or some other mechanism such as a tongue switch or electromyogram. Again, we are not proposing a specific design, but merely wish to indicate possible applications of our exoskeletal technology. Its major advantage is that it provides a very lightweight, very stiff structure, unlike other exoskeletal structures currently in existence.

Other possible applications include the patient undergoing physical therapy for muscle wasting. A number of powered mechanisms (Fig. 15-7) could be used in a clinic to provide physical therapy for several patients simultaneously when control is provided by a preprogrammed computer attended by one therapist. Through the selection of force sensors on the various sections of the arm, the particular therapy required for one individual patient could be programmed appropriately for his disorder.

DISCUSSION

Q. Have you done anything with damping in these joints to help reduce spasticity, or have you thought of a control where you could probably average out the control impetus by the patient?

A. No, the only thing we have done is what I have shown you in terms of the spacesuit skeletal concept, and that is in rather an early stage right now.

Q. Is there a similarity between one arm opposed to the other, so that something could be done, perhaps, to let the irregular motions of one help wipe out those of the other through special control means? Is there any similarity of the pattern of motion?

A. I am probably not qualified to answer that. Mel Sadoff is quite familiar with patterning and tasks of pilot performance. Mel, do you have any comment on this?

Sadoff: If I understand your question, I think that application would be very difficult, to use a motion of one to damp the other. I think you have to work on the arm that is involved.

Q. Is there a problem when it is used for an exoskeletal aid, when the exoskeletal device is motorized as a prosthesis, for example? How about the question of mechanical advantage?

A. If we assume that the slave could be a prosthesis, and it is powered, or it is driven through electrical power, we have a problem in that as you move through the range of motion of the joint and you get to the maximum range, where the bisector of a particular joint gets to 90 degrees of the longitudinal axis, it could self-destruct because the mechanical advantage theoretically goes to infinity since you are only overcoming friction of the bearing. The normal load is parallel to the axis of the bearing, so that you have an infinite mechanical advantage if you are powering the joint.

Q. I would like to compliment the author. I think it is a beautiful piece of mechanical design from the aesthetic standpoint, and from the conceptual standpoint as well. We have equipped two athetoid children with damping braces – a brace structure that contains dampers at three points. The dampers were about that big around and that wide, which is sort of the state of the art for observing the kinds of torques that it requires in situations. And with these braces, both of these children have been quite successful. They are able to go to school. But in terms of the actual design capability, they are very crude compared to the sort of things that we saw earlier. So I can't wait to see this kind of technology improved and brought to bear on the situation.

The other point is that it is quite feasible to stick pins into bones. It is done routinely in traction. The possibility of a mechanical device to move a joint and control it in a careful way in respect to speed, loads, time and displacement, and so on is just a direct implication of some of the things we saw. Following surgery, especially in the case of arthritis or rheumatoid arthritis, where joints have been reconstructed or where prosthetic joints are put in, there are very severe problems with the way in which the scar tissue forms, the way in which the tissue reorganizes during the healing process. There has been a great deal of discussion about the possibility of moving the joints, almost immediately following surgery, through controlled patterns in the directions that we would like to see them functionally developed, by such devices as we saw, and cause the prosthesis, for example, to grow into the bone and the tissue around it to grow in a direction that would enhance function at the end of the process, rather than the start of it. So your concept looks to me to be a very significant possibility.

Q. Why didn't this suit make it to space?

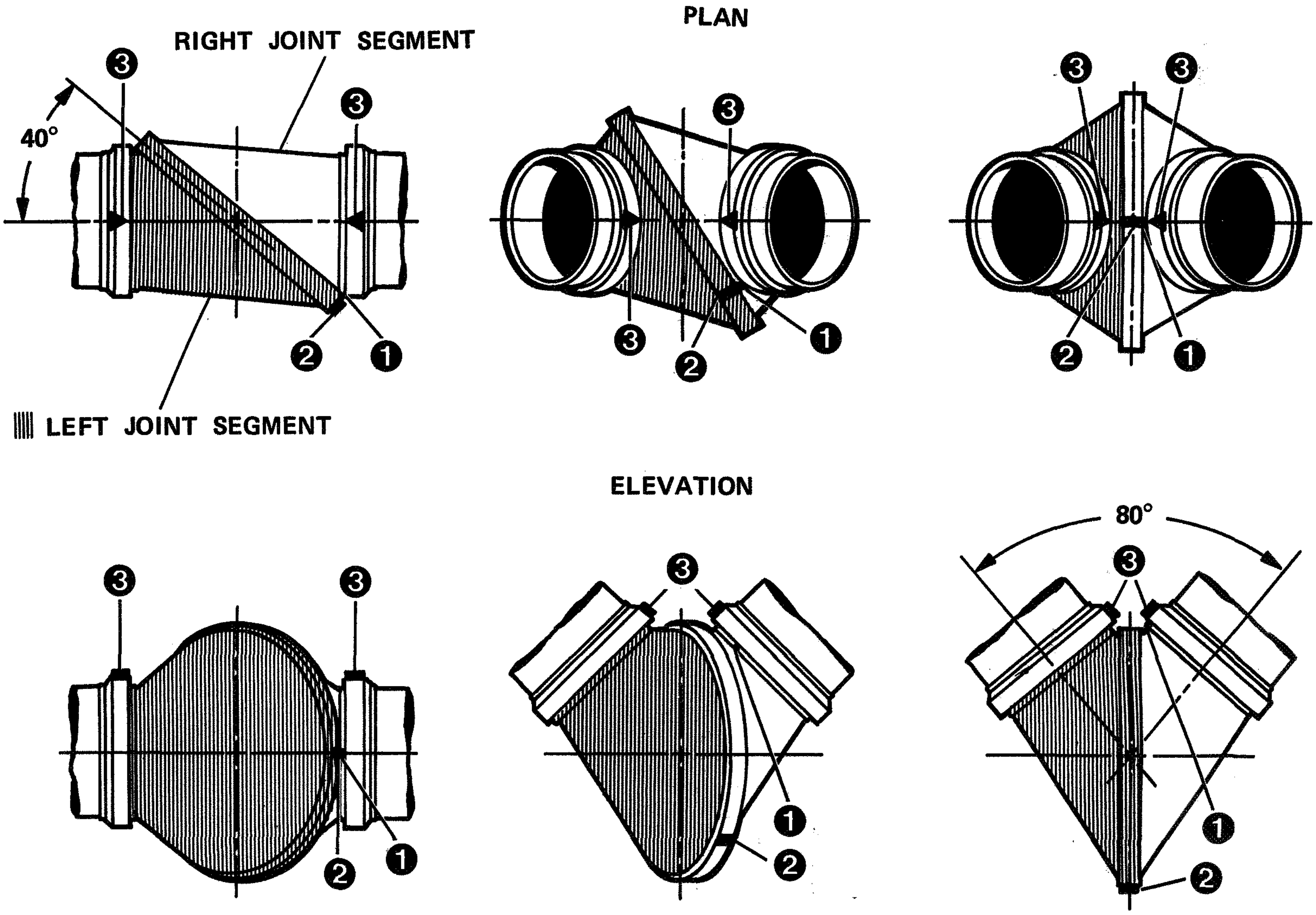
A. At Ames, we are charged with looking at advanced concepts. We don't develop flight hardware. This is done by our colleagues at the Manned Spacecraft Center. We are in close contact with the suit group down there. They had two advanced suits that were scheduled to be on Apollo 16 through 20 with the Lunar Rover. But with the curtailing of the later missions and also the reduction of the budget, these suits were not put into production. At the Manned Spacecraft Center they have used many of the concepts that we developed in this suit program.

Q. Is it still a problem to execute prehensile grasping and other movements in measured space suits?

A. Currently, it is a problem. Again, we hope we have the solution. First, we are raising the pressure in the suits to make them more compatible with the environment in future spacecraft or where the pressure will be probably 10 to 14 psi. To reduce the possibility of bends on rapid decompression, you have to have a suit that can at least maintain a pressure and provide mobility at 8 psi.

Now, there is still a problem with gloves. We have an excellent glove that was delivered to us by a contractor that incorporates a constant volume joint technology. We have tested it to 9 psi, and the mobility of the fingers is excellent. We are continuing this effort. In fact, the finger joint concept could be applicable for a prosthetic hand, since you can control the motion, depending on the mechanics of the system, to where just with air pressure it will grasp due to change in the pressure in the finger.

Sheridan: I just wanted to comment. I think the question about whether this particular suit made it into space or not is a little beside the point, for the requirements of a space suit are not necessarily those of an exoskeleton. I have examined some exoskeletons over the years, and this is far and away the cleverest and best functioning exoskeleton design I have ever seen. I really congratulate Mr. Vykukal on this design. I think it is great and very exciting.



1 RIGHT JOINT SEGMENT (REVOLVES TOWARD TOP)
2 LEFT JOINT SEGMENT (REVOLVES TOWARD BOTTOM)
3 CONSTANT

Fig. 15-1.– Stovepipe joint.

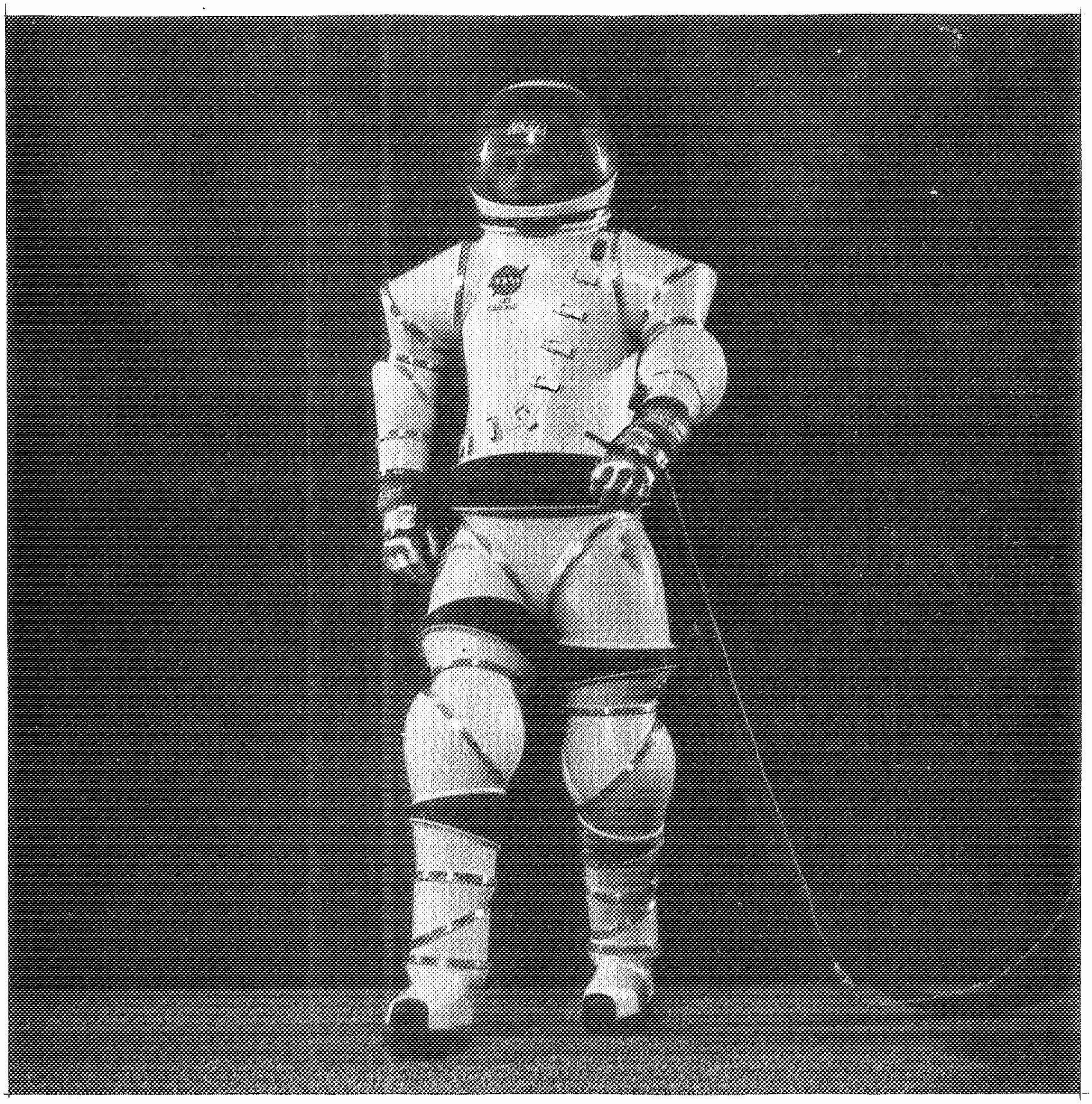


Fig. 15-2.– Ames AX-I hard space suite.

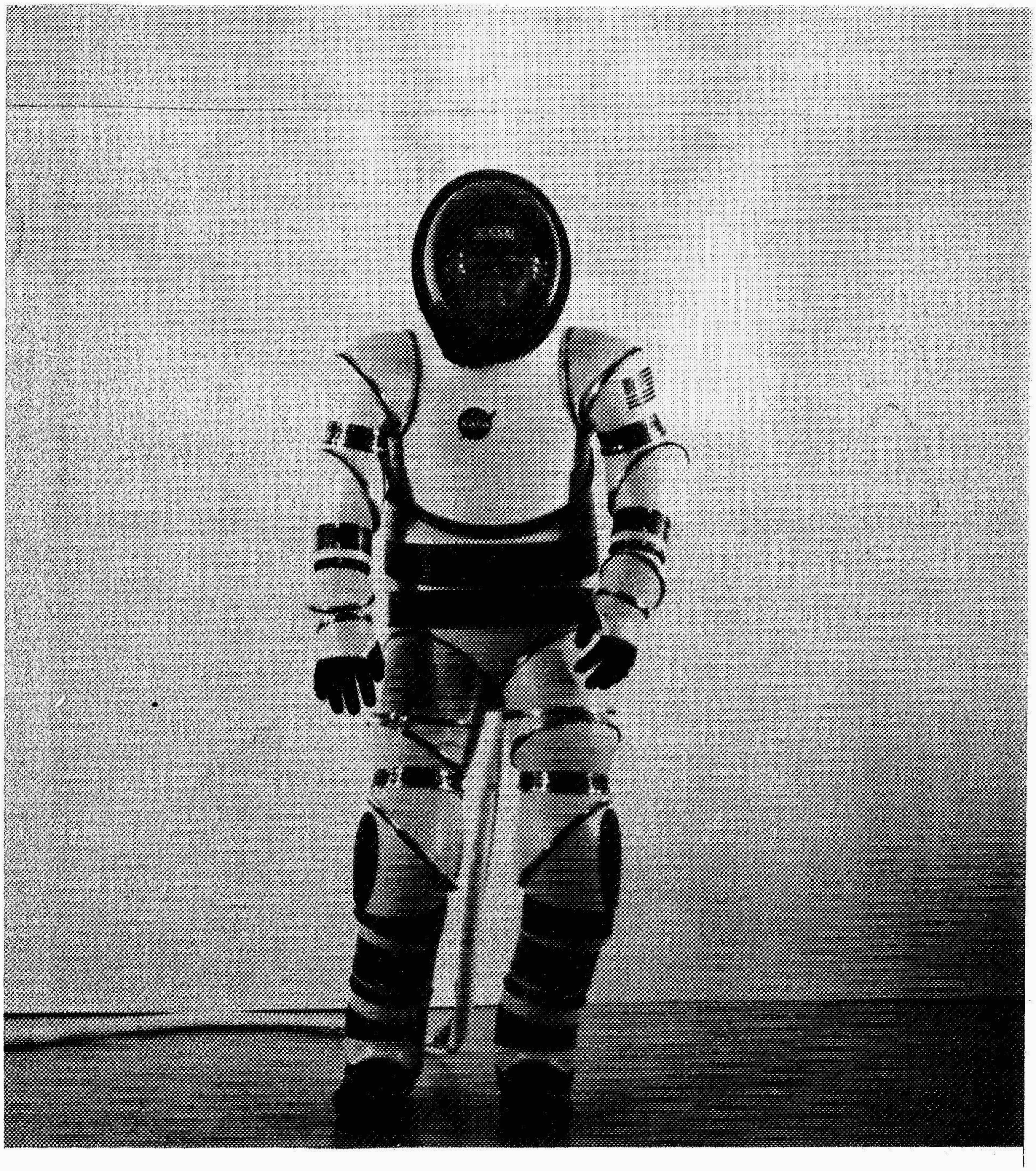


Fig. 15-3.– Ames AX-II hard space suit.

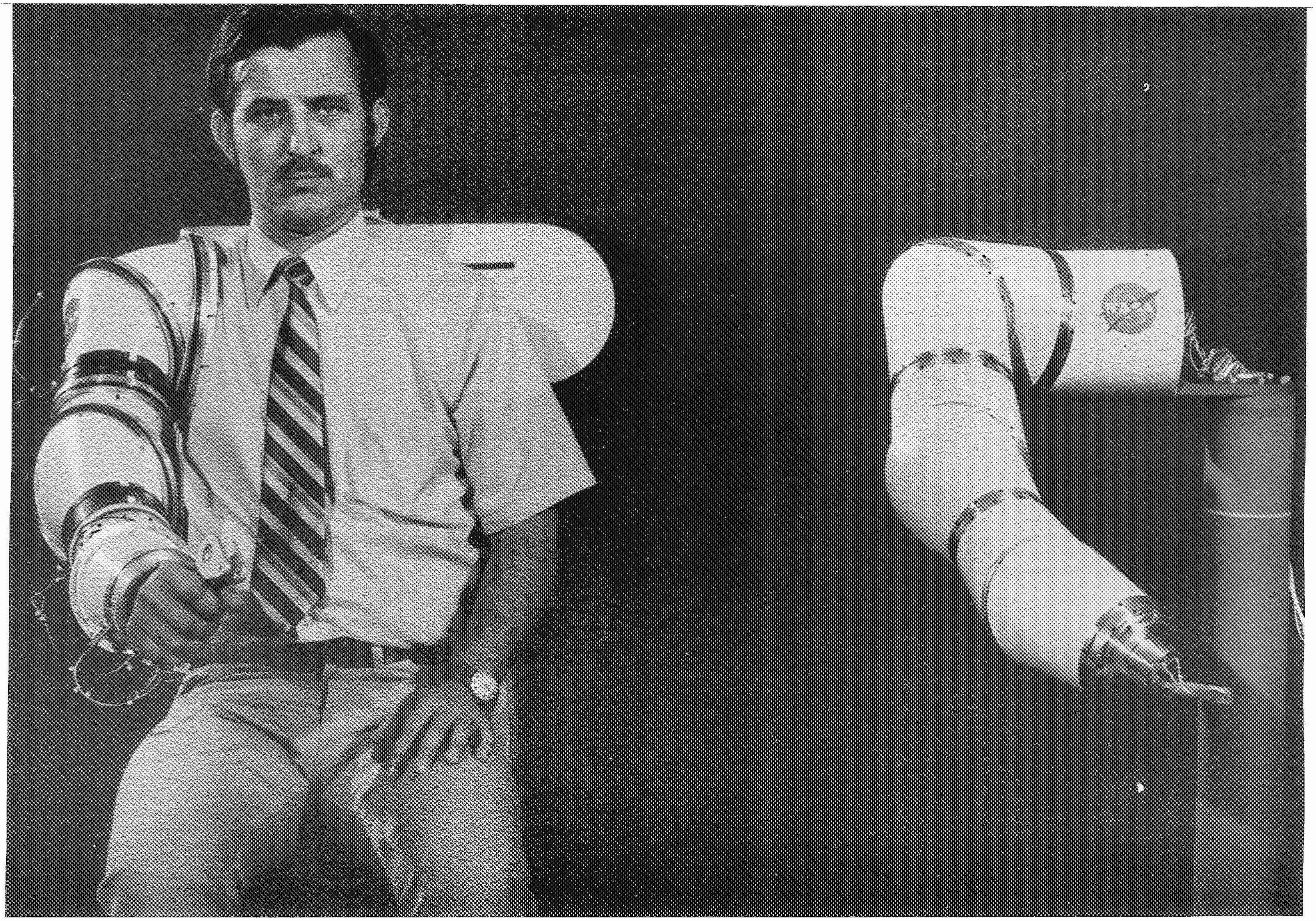


Fig. 15-4.– Ames remote manipulator system.

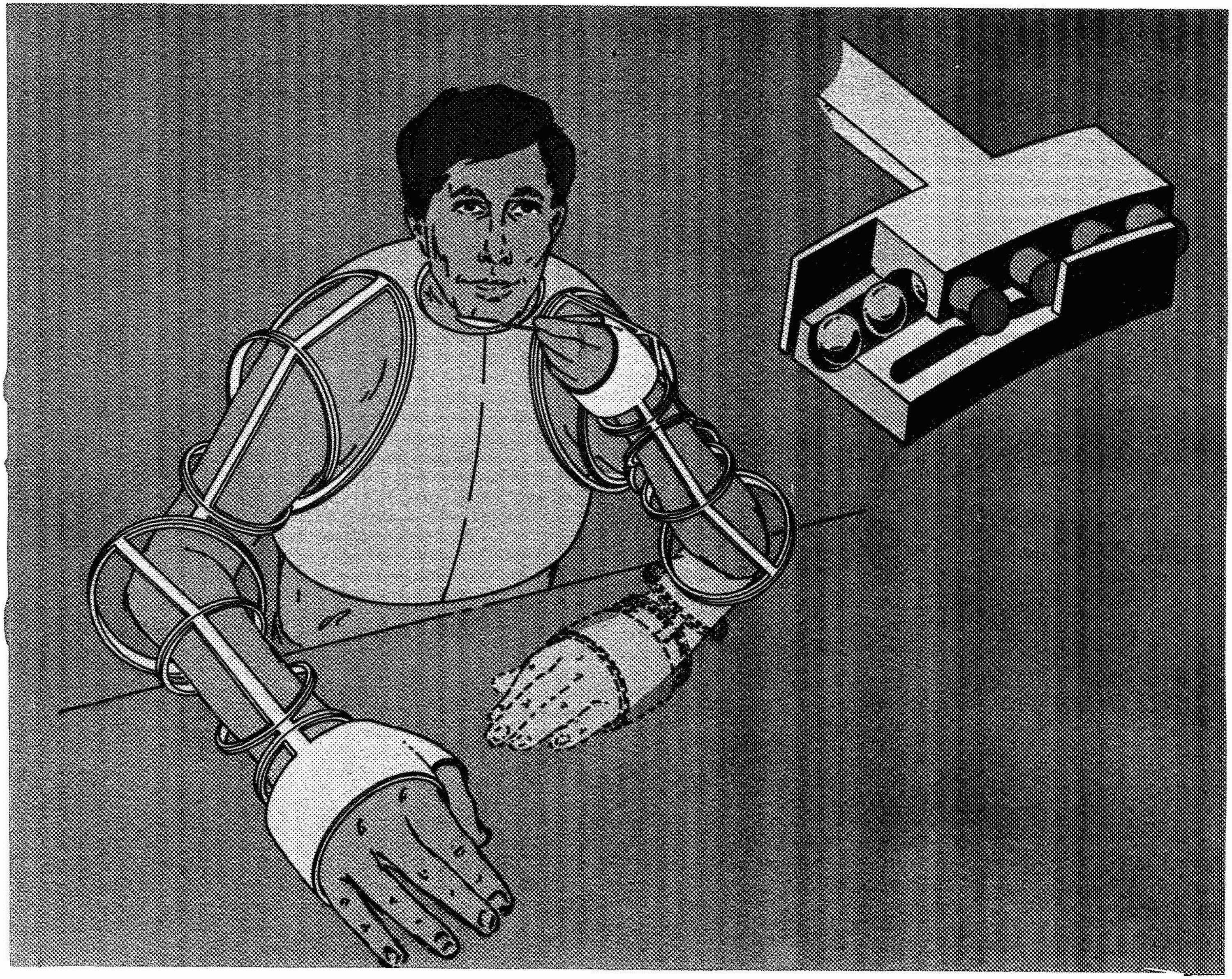


Fig. 15-5.– Exoskeletal damping brace.

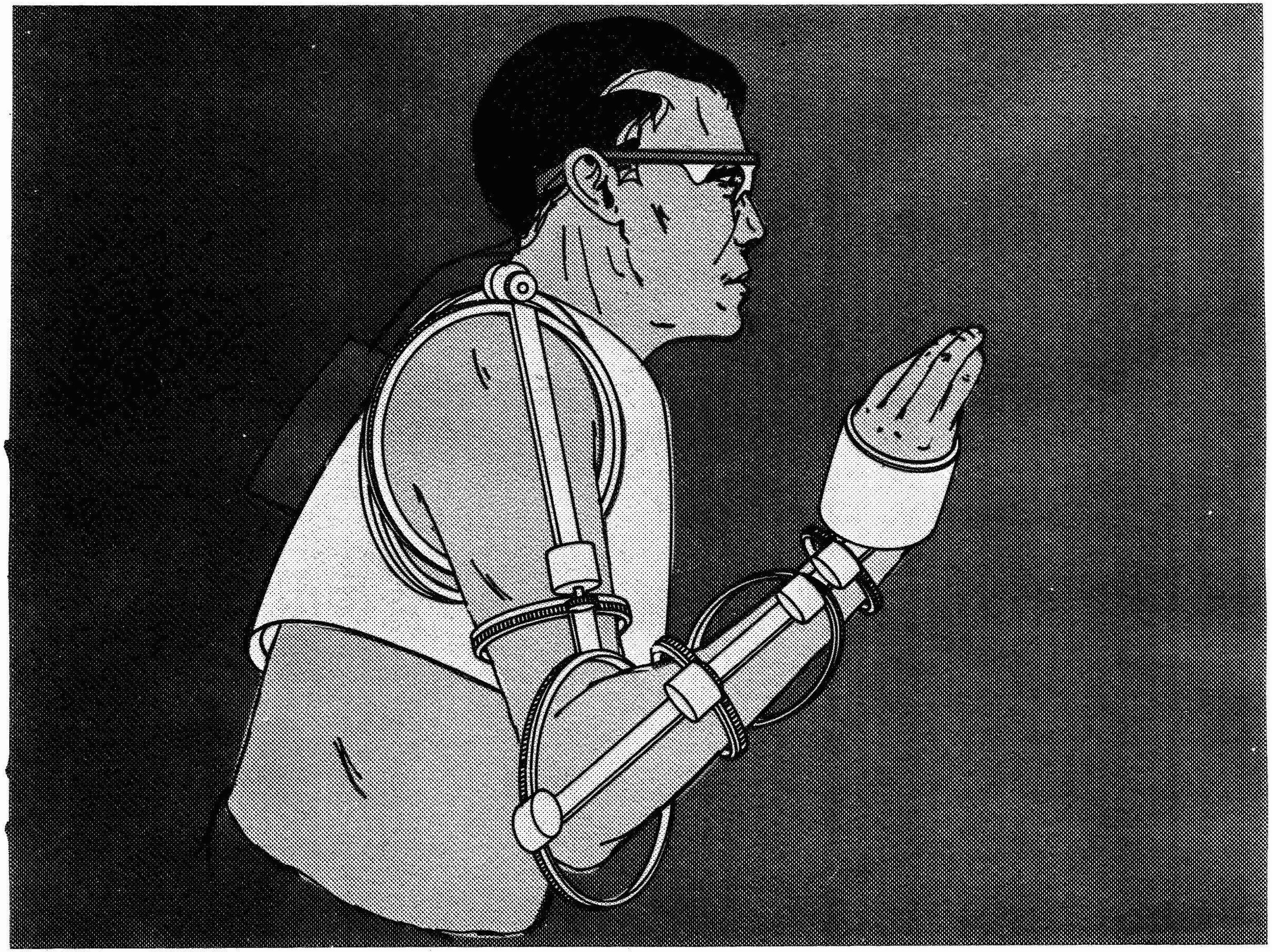


Fig. 15-6.– Exoskeletal powered brace.

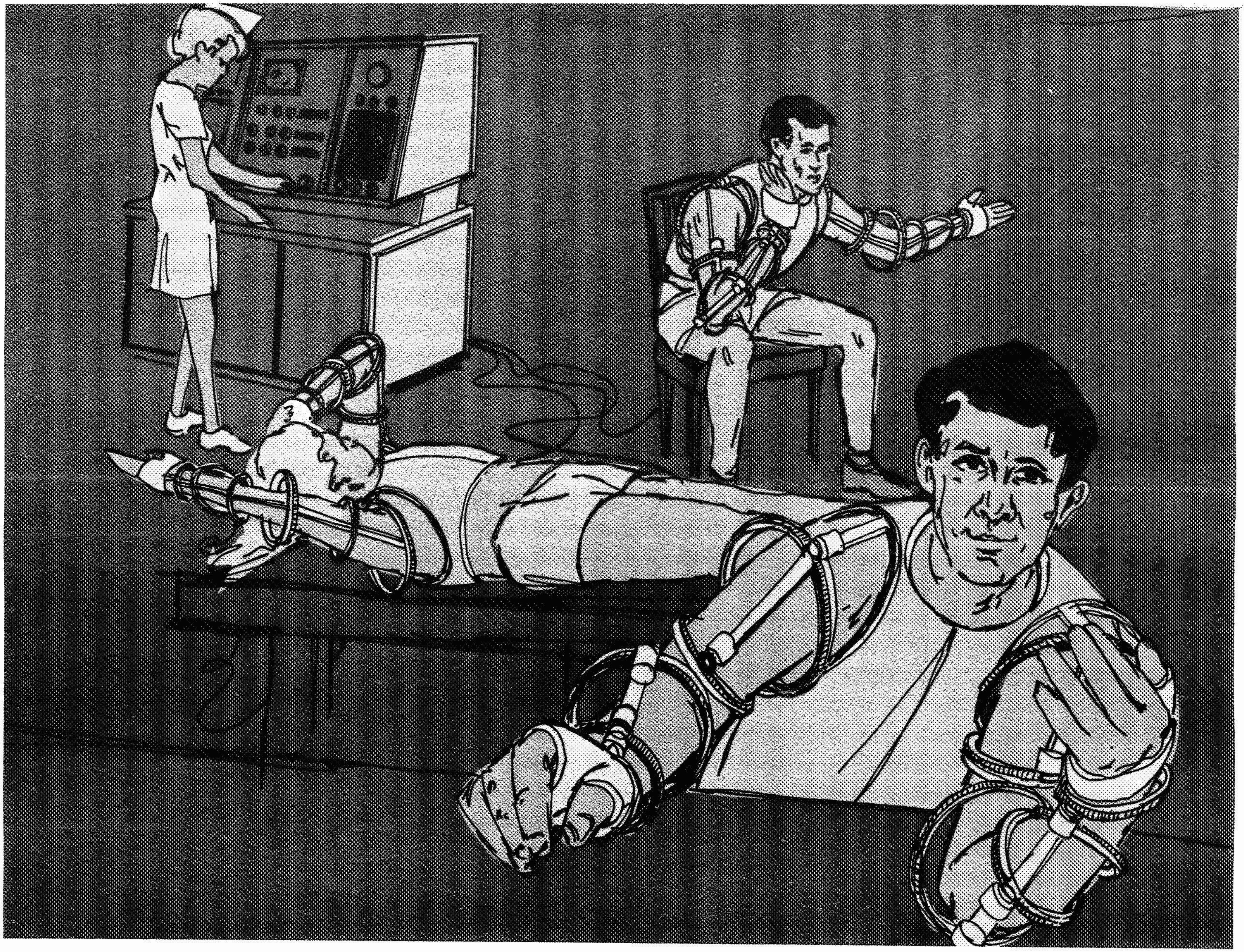


Fig. 15-7.– Therapy applications for powered brace.

Chapter 16

ARTIFICIAL SENSORY SYSTEMS

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In this chapter, we describe several artificial sensory systems, some of which are in a fairly advanced stage and some of which are in the early research stage.

OPTICAL–TACTILE IMAGE CONVERSION

We first consider an optical-to-tactile system used as a reading aid for the blind. The optical-to-tactile image converter, called *Optacon*, consists of two basic parts – a very small camera and a silicon retina. The camera looks at an area about the size of a letter space, which is imaged on the silicon retina.

The silicon retina for this application comprises 144 phototransistors, and was developed in the integrated circuits laboratory at Stanford University. The retina consists of 24 rows spaced 6 mils apart, and 6 columns spaced 12 mils apart, so that the entire silicon chip is something like 4 mm by 2 mm. This small size permits a nominal magnification in our camera of 1-to-1, which makes zoom optics very simple.

The camera is shown in Figure 16-1. It has been designed with a simple zoom adjustment on the front and has easily detachable optics, which make it adaptable for other purposes. The electronic signal from the camera, which conveys the information about the 144 image points, is transmitted to the box of electronics, which processes and displays this image on a tactile array of 144 vibrating pins. The vibration of each pin is produced by a piezoelectric crystal.

The piezoelectric crystal is constructed as a bender which is similar to a device used in phonograph cartridges; a voltage across it causes the reed to bend. We cantilever it at one end, so that it can push a pin up through the finger rest plate. We apply an alternating voltage to the reed so that the pin vibrates at 250 Hz. The vibration pattern produced by the array of reeds creates the image on a tactile screen, analogous to a TV screen. So the entire system produces a tactile image of 144 points of whatever the camera sees.

The Optacon is now in the production stage, and about 75 are planned for evaluation in some school systems within the next year. We have demonstrated its use for reading high level college mathematics, an example of material that not only has limited demand in Braille but also is very tedious to transcribe.

Given this level of achievement, we are continuing research to improve the reading performance achievable with the device. To date, the fastest anyone has been able to read with it is something like 80 words a minute; we think higher rates are possible, but the achievement of those higher rates has turned out to be a fairly difficult problem. To this end, we are experimenting with several variations of the display, but so far, we haven't got anything that is really promising.

On the other hand, the present device, as it stands, will permit a level of performance that can certainly be very useful to a lot of people. As an example, a very attractive vocational application for the Optacon is in the field of computer programming. Programs have been developed that can easily be read with an Optacon. A blind computer programmer at SRI uses the Optacon, as his only connection to listing and computer manuals; he is able to operate in a computation center that has made no provisions for a blind person at all, and with the same materials that a sighted computer programmer would use.

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We are making changes in the device to permit its manufacture at less cost, and are working on a number of attachments, primarily various lens attachments, that will extend its usefulness into other applications. These include the ability to read the key that has just been typed on the typewriter; handwriting by means of a writing instrument built into the camera; and the ability to read from various electronic readouts, ranging from numerical displays to CRT displays.

These are scientific and technological problems, and I am confident of our ability to eventually solve them. However, in agreement with Mann's comments (Chap. 13), I am much less confident of our ability to solve the remaining steps from a demonstration of a technological achievement to the delivery to a handicapped person. Given the achieved technological level, is there any hope that it can be exploited by the handicapped? Can reading aids such as this one be delivered to a significant number of blind people in some reasonable period of time, such as 5 or 10 years? If so, what will the process be? Who will prescribe it? Obviously, the role of the physician described by Reswick (Chap. 14) is not applicable here. Who does play the key role? What about the problems of training and of servicing such devices? To achieve the level of performance that we can demonstrate with the device takes not only some training but a great deal of practice. Who is doing the planning for these services, and setting the objectives and procedures for evaluating whether or not the objectives are achieved? The apparent lack of attention to these deployment problems is frustrating, and they are major concerns that must be addressed if we are going to raise the technological level of aids to the handicapped to twentieth century standards.

TELEOPERATOR TACTILE DISPLAYS

Dr. John Hill at SRI has been a major contributor to our research on tactile sensing and displays in the teleoperator field. This work is similar in some respects to the Optacon development effort outlined above.

Figure 16-2a shows a hand in which we have modified some tongs on a remote manipulator, so that they have tactile sensors. The tongs are not completed, and there are various kinds of tactile sensors on one tong. One type of sensor is shown on the outsides of the fingers of the tongs. A piece of conducting rubber is put around each condcuting plate and held away from the plate by a piece of sponge. A signal is generated whenever the conducting rubber touches the conducting plate. This is one type of touch sensor that is built into the hand.

Figure 16-2b shows the more complete unit with the tactile stimulators on the palm side of the fingers and the air jet stimulators arranged around the fingers; the air jet drivers are at the back.

Figure 16-3 shows another type of sensor – little whiskers at the extremities of the tongs, which are little rods of conducting rubber, pulled into a hole so that when the rod is bent, it touches the side of the hole and makes an electrical contact. This device affords a tremendous mechanical advantage in that very little force is required to indicate a contact.

The inside surface of each tong holds an array of 144 conductors embedded in an insulator and covered by a sheet of conducting rubber, as shown in the lower photo. Whenever the conducting rubber touches any one of the 144 conductors, an electrical signal is generated indicating which conductor was touched. This signal can be used to activate a corresponding tactile stimulator on the finger of the master unit or the person controlling the device.

The tactile stimulators of the control brace are arranged in 24 rows and 6 columns, and are the same type as used in the Optacon. This arrangement enables the person controlling the brace to perceive a pattern, or tactile image, of whatever the slide tongs are feeling, in terms of the contact area that is being made.

We can also have a visual display of the touch sensors built into the tongs. The sensors indicating contact for this block are displayed on the CRT. The sensors at the extremities of the tong can be displayed visually by intensifying lines here and there between the two tongs.

We have done limited experimentation with the arm. The task was to pick up a block. Using an earlier version of this system, we were able to show that many fewer mistakes were made in picking up something and grasping with tactile feedback than without.

We have also been exploring the same task, but with a time delay, which is of interest. The time delay is of interest for NASA applications, such as controlling arms on the moon. So this is the same kind of control, operated through a time delay.

Using the computer we can experiment with the tradeoffs between all-automatic manipulation and man-controlled manipulation to determine the best assignments of the various tasks between the man the the computer. There are several ways of operating the arm: through computer control, through the control brace, and by means of knobs.

We gave the computer the task of unscrewing a nut from a bolt. A test position was just established in the computer and the algorithm it uses for unscrewing the nut is to make a turn of the nut and then test to see if it has gotten the nut off the bolt; if it hasn't, it will make another turn. If it has, it will take the nut and place it in a box.

Figure 16-4 shows the data from an experiment comparing the time to complete this task with and without a time delay. The data show that there is a tremendous advantage under combined manual and computer control when you have a large time delay in the system.

The kind of research outlined here is directed at some space applications, and we have not yet been able to consider some of the applications of this technology to the handicapped. Clearly, there is potential for such applications, and the prospect of pursuing them is very exciting.

DISCUSSION

Q. I have a suggestion, Dr. Bliss. Just for fun, there is a possibility that when you are testing for taking the nut off, it would catch, and when you let go of it, it might jog and fall. So after you test for it being engaged or disengaged, could you not turn it back clockwise one-sixth of a turn and then let go? This would eliminate the possibility of the nut falling off.

A. Right; I see your point. Yes.

Q. In the Optacon, can a normally sighted person recognize characters with the tips of his fingers without a lot of training?

A. Certainly some characters. I think almost anyone, and almost immediately, can recognize letters such as C, O, U, E. Certain letters are more difficult and require some practice, like lower case a, e, s, to make those distinctions. But many people can make the distinctions almost immediately.

Q. How large is the readout matrix?

A. It is about an inch by half an inch. The rows are 45 mils apart and the columns are 90 mils apart. So that spans an area that is bigger than just the distal flange of the finger, and comes a little bit down into the middle flange.

Q. I was recently a member of the site visiting team of this project and I don't know whether Jim (Bliss) and Loren* know this or not, but one of the more suspicious members of the team, when the subject was demonstrating, placed a cardboard card in front of his eyes so there was no possibility of him seeing the page and then chose a page at random. And he performed better or at least as well as he did today.

Q. Is it likely that there would be frequency discrimination to provide a further variable that one could use to represent intensity changes or color changes, for example? We know very well that the central neural response to tactile stimuli changes its neurophysiological pattern as you get up to high frequencies. And one would imagine there would be a wide range of discrimination with very powerful information transfer. Have you considered this possibility and tried it at all?

A. We have considered it, and we have done some experiments along those lines. It certainly is true that you can distinguish between various frequencies and you could use that dimension for information about coloring as well as intensity. We haven't done nearly as much work on those dimensions as we have on the dimension of spatial locus, which is what we are using here. I think the dimension of spatial locus is the most potent for displaying, and it is also the most natural for something such as the reading problem. To get into those other problems, you also bring in such mechanical problems as how to ensure consistent and effective contact with the skin.

There is also the problem that fine discrimination in frequency is not orthogonal to fine intensity discriminations. And they are very often confused.

Q. What is the range of letter size that you can read?

A. I think the range is about 5-to-1. The zoom lens works over about a 2.5 to 1 range, but you can tolerate about a 2-to-1 size on the array itself.

Q. Can you read the headline of a newspaper, for example?

A. The way you would read a headline of a newspaper would be different in that you would see part of the letter at a time. But using the sense of scanning out the letter, it is slower, but it can be read.

Q. You had an auditory tone. Is that an important part of the function?

A. No. The main reason I know it is not an important part of the function is that we have trained a totally deaf, blind person to read with it. But there is certainly some information in the auditory tone, and I don't consider this objectionable. The information is that the device is working and that you can certainly tell the difference in the sound when a period goes by and when a big letter goes by, just from the intensity. So it does give some information, but it is certainly not necessary.

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*Note: Mr. Loren Schoof was the blind subject who demonstrated the Optacon to the conference.

Q. You were asked a number of questions before with regard to manufacturing and distribution. Did you arrive at any conclusions?

A. Well, we are proceeding in that direction in that we are producing now some devices for a field trial evaluation. But what really concerns me is that I don't see anyone looking ahead. When we do that field trial evaluation, I would be very surprised if it didn't come out very successfully, but I am not sure anyone is looking at what will happen next. The problem of actually disseminating this kind of technology to a significant number of blind people is formidable and not well appreciated.

Q. Who do you think should do it?

A. That is a good question. And it is not clear to me who is going to take that kind of responsibility or if that can be a natural function of the free enterprise system. I think someone, perhaps a government agency, is going to have to take some kind of role or responsibility.

Q. I had a comment that was very much along the lines of the last question. I think very real thought has to be given, probably by the people here, as to what sort of dissemination there will be with units such as yours. There are others that have been discussed at this meeting. How is it that they are going to be distributed to the people who need them? Just making them and operating them is a lot of fun for us to sit here and watch, but they don't do the people that they are made for any good. I think a group possibly should even be formed that would go into the possibilities of whether the free enterprise system or government would be able to distribute these devices to people who need them.

A. Right; and I wanted to make the point, too, that this is somewhat different from a lot of other devices being discussed here, in that I doubt that the medical profession will play the same kind of role as it would naturally play.

Q. Right now, you don't know whether that is an asset or a liability.

A. Right.

Q. This question relates to the spatial orientation, the ability to find where the next line is and where it begins, relative to pattern recognition. Has any thought been given as to how to aid the person using the device to achieve good continuity in getting information across, so that he doesn't have to scan and search the whole page, or around and up and down until he finally finds the beginning of the next line?

A. When we start training someone with the Optacon, we use a tracking aid, the purpose of which is to aid him in finding the next line and to stay on a line. But I think Loren Schoof may want to comment on this, that once someone is trained, it is better to have no aid than to have an aid. The freehand operation of the device turned out to be surprisingly effective. – Loren, do you find much problem?

A. Mr. Schoof (The blind subject who demonstrated the Optacon): Well, you find that the tracking aid, although it is very nice for keeping you on the line, turns out actually to slow you down by the time you get much skill with it. What happens is, in reading, for example, you may want to go slightly above or slightly below the line for various reasons. You may expect part of something. A specific example is when I was reading that summation symbol (Σ). You could not see all of the capital sigma there, and what is more, there is information directly above and directly below the sigma. If you have the tracking aid, you have to release it and move it, all of which slows you down. And the same is true when in fact you are changing lines.

Q. I would like to make a comment about this business of getting these devices to people who can use them. I think it is an extremely important one. To say that nobody is thinking about it isn't quite fair. I know quite a few people are. There is considerable precedent for things like this in prosthetics, where sophisticated things have been developed, and as a rule, after a device has been evaluated and its usefulness demonstrated, then schools have to be set up and people have been brought in for training. So it does get down to the patient. It is not quite as bleak as you think.

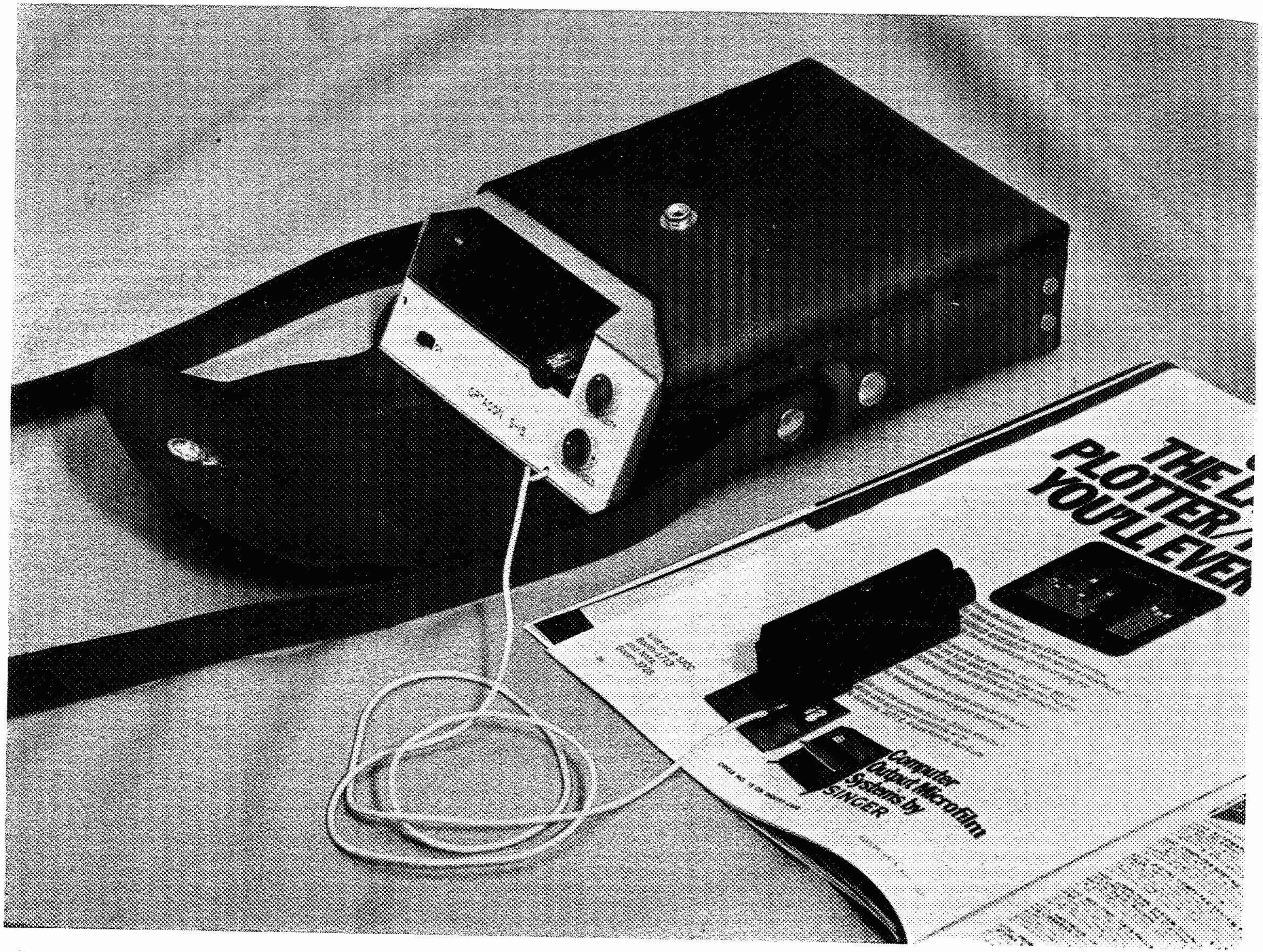
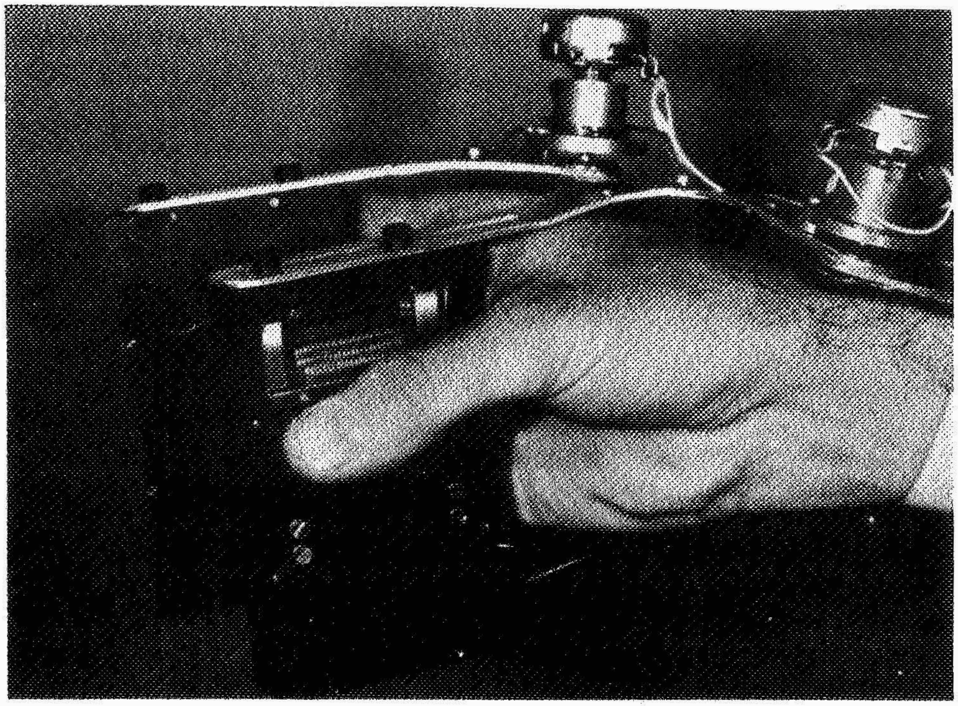
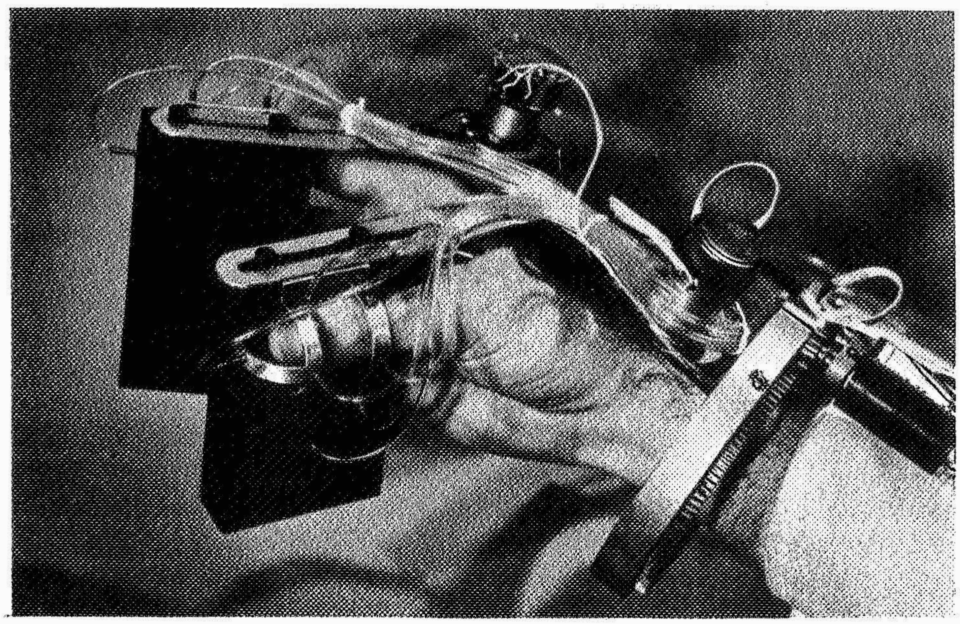


Fig. 16-1.– "The Optacon."



(a) Piezoelectric vibrators



(b) Air jet stimulators

Fig. 16-2.– Tactile stimulators on the hand controller. The upper photograph shows the array of 6 X 24 piezoelectric vibrators positioned under the thumb. The lower photo shows the same hand controller with seven air jets in place on each finger.

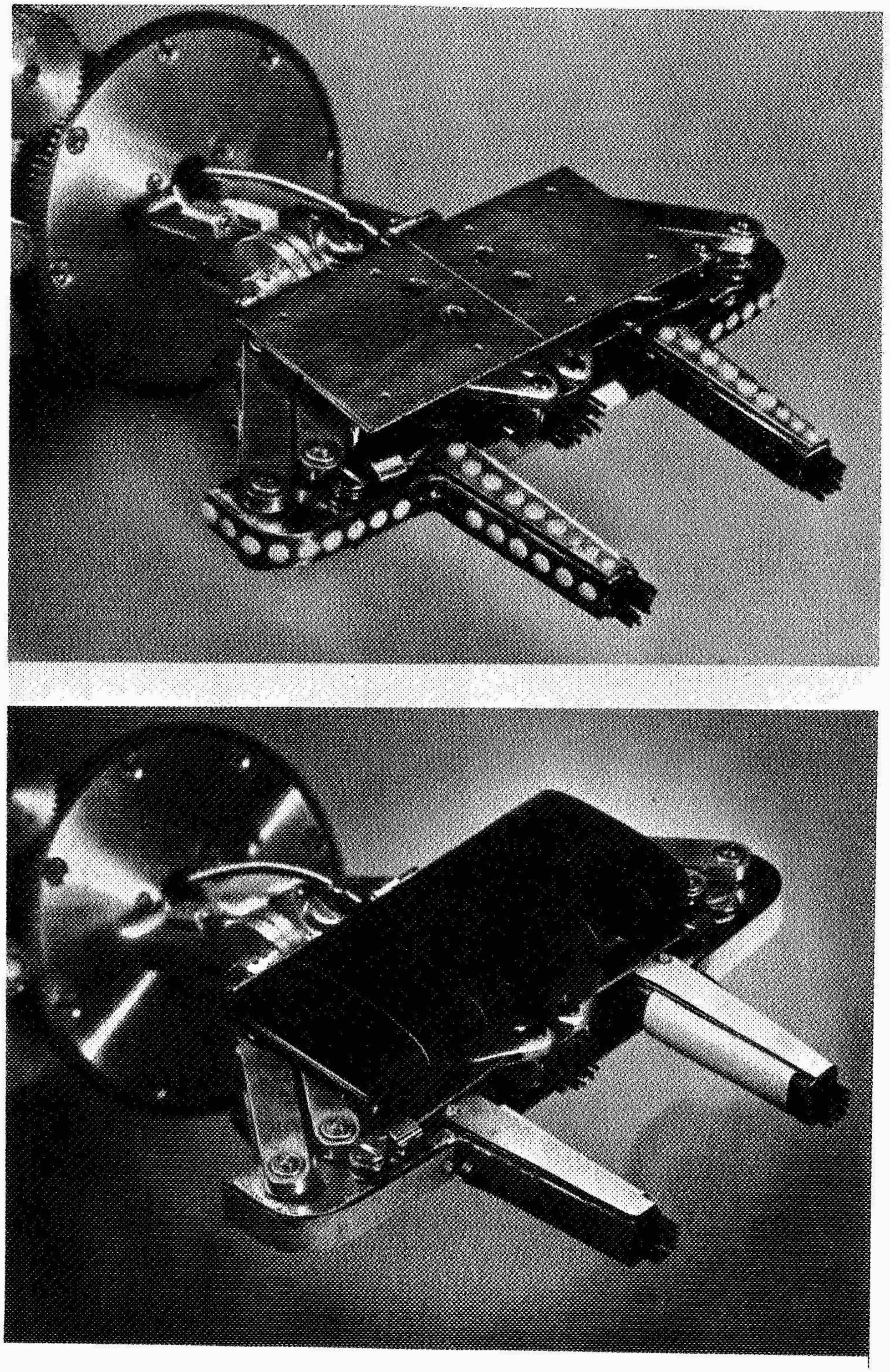


Fig. 16-3.– Touch sensors on Rancho Hand. Upper photo shows contact sensors bonded to tongue and wrist. Both whisker and planar sensors use flexible conducting rubber membranes. Lower photo shows finished assembly with conducting rubber covers in position.

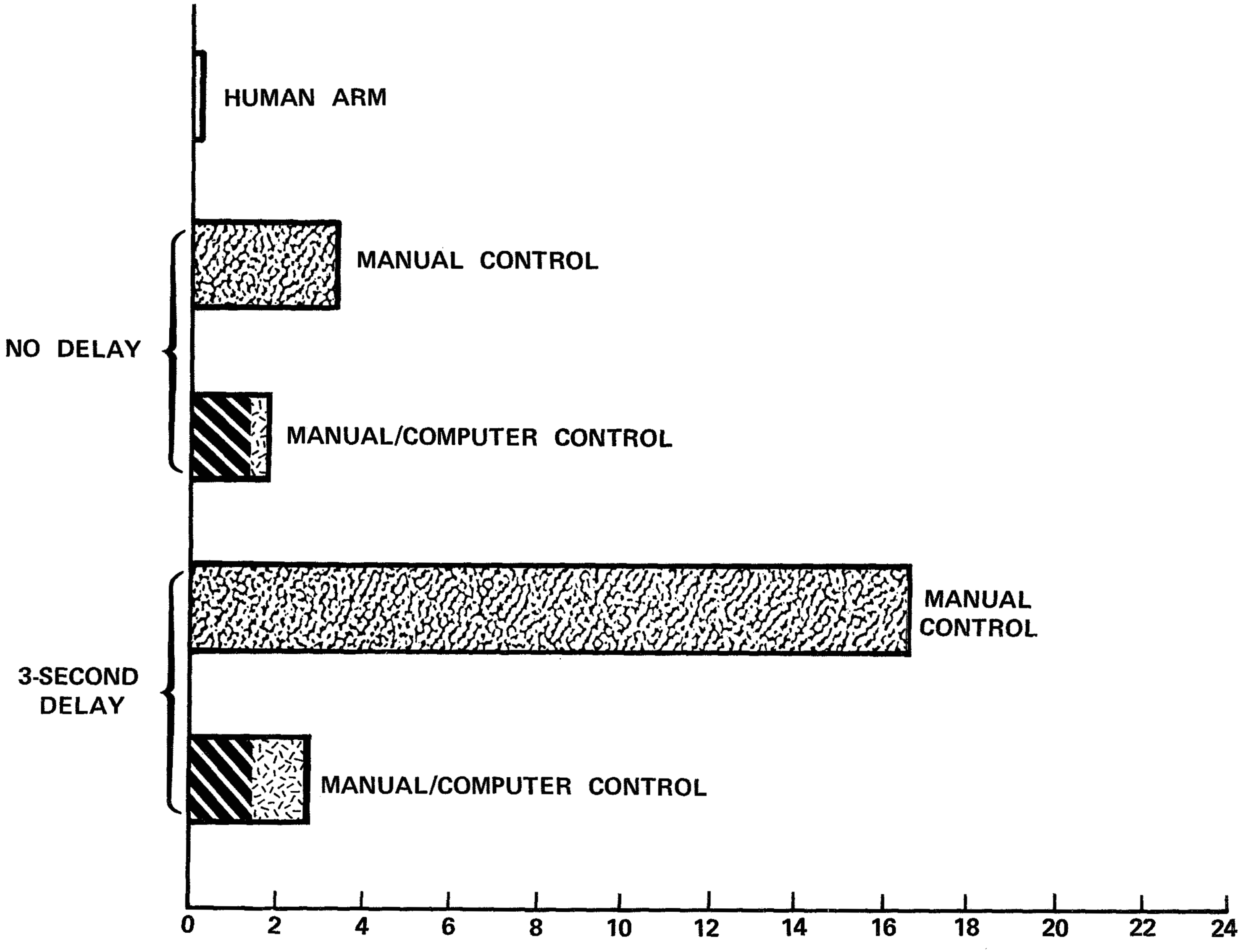


Fig. 16-4.– Comparison between manual and computer-assisted manual control. The time taken to perform the task directly with a human hand is shown only for comparison. Computer-assisted times are broken into two parts: the time required by the program, which is the same in both delay conditions, and the time required by the manual portion.

Chapter 17

MODELS OF THE VESTIBULAR SYSTEM AND POSTURAL CONTROL

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In this chapter, we discuss applications of control theory and systems analysis to the problem of orientation and posture control, with the possible long-range goals of contributing to the development of hardware for rehabilitation of the handicapped.

CONTROL THEORY AND SYSTEMS ANALYSIS

The staff in our laboratory at MIT are mostly aeronautical engineers and electrical engineers trained in control theory. We began by applying control theory to problems of man-machine systems – orientation and vertigo. This led us quickly to the need to study some of the underlying physiological mechanisms, especially the visual and vestibular systems. We found it useful to examine the orientation system in patients with a variety of labyrinthine defects. Naturally, once we had some patients in the laboratory, we became interested in the patients themselves, and this has led us into our current work of attempting to develop clinical test procedures. At that stage, we began to work most closely with Dr. Weiss and his associates at the Massachusetts Eye and Ear Infirmary.

The vestibular apparatus (Fig. 17-1) includes three roughly orthogonal semicircular canals in each inner ear. These thin tubes are filled with endolymph. The geometry of the canals permits the sensation of head rotations.

The other functional parts of the vestibular apparatus are the otoliths – in the utriculus and the sacculus – which serve a function analogous to that of linear accelerometers. Engineers think of the vestibular system as a low-grade inertial reference system in which the semicircular canals serve the function of gyros in measuring angular rotations, and the otoliths, or linear accelerometers, serve the function of measuring orientations with respect to the vertical.

Figure 17-2 gives the control engineer's view of this same system, treated as an input-output system. We attempt to describe it mathematically to try to understand its operation and produce experiments that will help us get at the underlying physiological mechanisms in the semicircular canals and otoliths. The input-output relations for this sensory system are rather simple. Angular acceleration and gravito-inertial forces on the head are the inputs. The outputs that we can measure without penetrating the skin, leaving aside electrophysiological measures for the moment, are the following: nystagmus, perceived orientation measured psychophysically, postural reflexes, and control and compensation. If a man is attempting to fly an airplane, ride a bicycle, or stabilize a simulator, we can measure the manual control that he produces. It is clear that the outputs of the vestibular apparatus, the canals and the otoliths, are combined with important nonvestibular inputs (principally visual, tactile, and proprioceptive) in the central nervous system in leading to perceived orientation as well as other outputs.

Some of the details of experiments we have done in relating angular acceleration to these outputs are reviewed in reference 1. The experiments involve the linear and angular motion of people, with or without visual cues, in an attempt to refine these mathematical models. Figure 17-3 shows our current model for the operation of the semicircular canals. We try to use information about dimensions and physical properties of the system, to build up such mathematical models. In this case, the model relates angular acceleration of the head to displacement of endolymph, taking into account the viscous force associated with flow of endolymph, the spring forces associated deflections of the cupula, some of the neural processes representing adaptation, and the different aspects of thresholds that we observed. The threshold, of course, depends on whether we are measuring nystagmus, a subjective sensation, or a variety of illusions.

These models serve a useful purpose. They predict rather accurately the average response of normal subjects to different kinds of spinning stimuli. I will quickly review some of the kinds of responses that are predicted accurately.

A common one is the impulsive response, where a subject is spun at a constant angular velocity and is brought suddenly to a stop. This is the test that is commonly used clinically. As shown in Figure 17-4, if you spin at a constant angular velocity and come to a sudden stop, the sensation and nystagmus are consistent with moving in the opposite direction following the stop, slowing down to zero, and, if the original stimulus is strong enough, producing a brief second effect, which dies out. In some cases, one observes still further reversals, which are not predicted by this model.

In a constant angular acceleration test, people are spun at faster and faster speeds. The ordinate in Figure 17-5 represents the actual angular velocity, and the lower curve on the graph represents the nystagmus slow phase velocity, which builds up to a maximum and decays. Similarly, the subjective sensation of rotation, as shown by the upper line, builds up to a maximum and decays.

This constant angular acceleration stimulus can also be used to measure the time it takes for the subject to correctly identify the direction in which he is accelerated. The measurements of Clark and Stewart at NASA-Ames are perhaps the most accurate measurements of the thresholds of angular acceleration. The relationship of latency time to the acceleration stimulus, shown in Figure 17-6, serves as perhaps the only check on the nonlinearity in the model.

No control engineer worth his salt would try to identify a system without exposing it to a sinusoidal stimulus. Figure 17-7 is such a case taken from Meiry's thesis in which the subject was oscillated about a vertical axis, represented by the lower curve. He demonstrates a typical pattern of vestibular nystagmus, in which the slow phase of eye velocity attempts to stabilize the eye in space. That is, as you are moving to the left, your eye slowly compensates to the right. By piecing together all the slow phase segments, and throwing out the fast phases, we obtain a "cumulative" eye position curve that is roughly sinusoidal. We can compare the phase and amplitude of the eye position with the stimulus to get a frequency response of the vestibulo-ocular reflex, which again is well matched by the models, except for some minor problems at high frequencies. As Geoffrey Melvill Jones pointed out some years ago, the semicircular canals operate rather well as velocity transducers over the physiological range of head movements.

The story on the otoliths or the linear acceleration sensors is not nearly as clear. We have proposed a mathematical model in which we have less than full confidence, which relates gravity and linear acceleration to perceived acceleration or tilt with respect to the vertical. One type of available information is perceived linear velocity. Figure 17-8 is a frequency response curve for the linear acceleration sensors. If you oscillate someone on a linear track and ask him to indicate the direction in which he thinks he is moving, you can examine the phase relationship between his subjective sensation of velocity and the actual motion. One can also examine counterrolling – a counterrotation of the eye about the optic axis – and that information is also indicated on the frequency response.

We returned to the original problem of human orientation and postural control with a rather simple question. (As we know, these supposedly simple questions in physiology inevitably turn out to be complicated.)

In a doctoral thesis by Lewis Nashner, we examined the question of control of fore and aft sway about the axis through the ankles, eliminating all the motion about the knees and the hips. We asked how a human manages to stand upright when he is an unstable system on a narrow base. With the center of gravity far above the fulcrum, he remains upright without acting like a tin soldier. The outline for the kind of a systems study that Nashner undertook is shown in the block diagram of Figure 17-9. We start with simple models of the human body represented as a inverted pendulum. The forces exerted on it by the appropriate muscles are generated through the spinal centers, based on direct commands from higher centers, force feedback through the tendon organs, position feedback from the muscle spindles, and the important higher center feedbacks, visual feedback, exteroceptive feedback, and vestibular feedback, including feedback from both the otoliths and the semicircular canals. We ask first of all how normal subjects use these various feedback loops in postural control and then how patients with neurological disorders can be viewed in terms of the changes in these feedback loops, and the compensations that are used in substituting other loops.

In the next section, Weiss discusses the efforts to extend this kind of work to the neurological clinical applications.

EXPERIMENTS IN THE NEUROPHYSIOLOGY OF POSTURAL CONTROL

Positional control in the human organism is an extremely complex mechanism. One need merely look at the extremely variable stances and complicated motions performed by athletes to recognize that the static and dynamic stability of the organism involves a large number of coordinated systems, both sensory and motor, to achieve such a highly integrated level of function. A given posture may be quite stable in one situation and rather unstable in another. Thus, posture must be considered not only in terms of what it is at any given moment but how it fits into the time sequence of static stability and dynamic motion. A person in a static posture is not rigid but has a number of complexly interacting sensory and motor activities going on to preserve the stability of the system for a period of time. There are many motions, then, that contribute to the seeming static stability. The analysis of this tremendous complexity is begun most easily by looking at the human organism in a statically stable condition trying to preserve this state against small external imbalancing forces.

We will consider briefly two experiments from our laboratory that have utilized this approach. In the first experiment, carried out primarily by Lewis Nashner, each subject was placed on a platform (Fig. 17-10). The subject stands with the feet slightly apart to minimize lateral sway. Sway in the sagittal plane is measured by means of a belt slung around the hips. We also measured the pressures on the corners of the platform. Two forms of platform disturbances were used. In one, there was a slight upward or downward tilting of the front of the platform, producing motion at the ankles. A second form of disturbance was based on the forward or backward translation of the platform. This could be done simultaneously with movement of the platform in such a way that there was no effective change in ankle angle. The responses of the subject, whose task was to maintain postural stability, were ascertained in conditions of eyes opened and of eyes closed.

The reasoning underlying this experiment was that several types of sensory input seem related to the maintenance of erect posture. These include visual stimuli, vestibular stimuli, both of the semicircular canals and of the utricle, proprioceptive stimuli in the ankle, stretch reflexes in the tendons and the muscles, and conceivably also the change in pressure stimuli in the foot at the point of contact with the platform. The change in body angle from the vertical and the changes in pressures on the platform were measured over time relative to the introduction of a disturbing impulse. Eye closure could be used to eliminate visual input. Maintenance of constant ankle angle could be used to eliminate proprioceptive input. A subject who had had bilateral acoustic neuromas surgically excised, totally eliminating vestibular input, was used for testing the results of loss of such input. In this subject, it also became possible then to eliminate visual input as well in order to assess how the remaining proprioceptive impulses could be utilized to maintain postural stability.

The findings of this study were summarized by Nashner as follows:

> During quiet standing on a rigid surface, ankle reflex gain is about one-third that necessary for postural stability. Ankle reflexes, however, are adequate to fully stabilize very small deflections due to the presence of "stiction" forces acting between fibers in intra- and extrafusal muscle fibers. Quiet standing is punctuated by frequent transients during which the subject "breaks out" of static reflex stability and begins to diverge. A kinesthetic threshold is reached, commanding a transient multiplicative increase in reflex gain proportional to disturbance amplitude. A static sense, either vision or utricle otolith, is necessary to correct slow drift of this reflex/kinesthetic control loop.
>
> When reflex and visual feedback are removed, the vestibular sensor are able to fully stabilize posture. The utricle otoliths and semicircular canals act as frequency selective feedback sensors. The canals detect sway divergence and initiate corrective postural responses. The utricle otoliths provide a static vertical reference to stabilize slow drift of the canal control loop. Otolith cues are shown to be ambiguous at higher frequencies because of interactions between linear motion and gravitational stimuli.
>
> Control strategy is observed in one subject as mentioned earlier with complete loss of vestibular function but with normal motor control. When the eyes are open, the subject shows a reflex/kinesthetic control strategy which is very nearly normal. The subject is also able to stand with eyes closed; however, this required great effort. Tests show eyes-closed control strategy to be radically different. Extensor reflex gains were increased six-fold, allocating almost complete control of function to reflex "rigidity."

The other experiment, performed by Tole and Weiss, concerned the effect of galvanic vestibular stimulation on the stability of the vestibular system. The subject was seated in an enclosed, darkened Barany chair, which was pseudorandomly oscillated over a range of 540°. The subject had a control switch with which he could null the movement of the chair. Previous experiments had shown that there is a tendency of the subject to allow the chair to drift in a preferred direction, almost always to the right, indicating that the thresholds of sensation of rotation to right and left are not balanced perfectly. We superimposed on this system galvanic current by means of electrodes on the mastoid processes and the nape of the neck, applied either monaurally or binaurally, with different polarities. An example of one such two-minute run is given in Figure 17-11, which shows a typical chair position, eye position, and chair command signal curve. Superimposed on the chair command signal is the subject's operation of his switch, which acts to alter the quasirandom input signal to the chair. In this particular run, the galvanic stimulus was a unipolar left anodic current at 1600 μa. It will be noted that there is a progressive deviation of the chair from its zero position to the left. The eye position record shows primarily right-beating nystagmus, and the chair command signal shows the subject's use of the left turning (therefore sensing right rotation) side of the switch almost exclusively.

Six levels of current were used for stimulation, ranging from 100 to 3,000 μa. Eye movements were also monitored, and the results were processed through a computer program which summed the slow phase portions of nystagmus. A plot of the results is shown in Figure 17-12. The plot shows the apparent bias below the threshold of the galvanic current effect. Threshold is set somewhat arbitrarily at 600 μa; statistically there seemed to be no effect at 400 μa, but a definite statistical effect could be demonstrated at 800 μa. A least-mean-squares linear plot was then made through this point and the three intensity means above threshold. The findings suggest that galvanic vestibular stimulation has a direct effect on rotational thresholds. The slope of the fitted straight line provides a gain of 0.0007°/sec/μa. Thus, it is possible to make quantitative comparison between rotational and galvanic vestibular stimulation.

The slow phase eye position data were treated the same way, but no significant statistical differences were found. An important point not obvious at first but clearly evident from the statistical analysis was that anodic and cathodic stimulations were equally effective in producing rotational bias, differing only in the direction of effect. This became evident only after we subtracted out the spontaneous rotation that occurred in the absence of galvanic stimulation. Also, binaural and monaural stimulations were equally effective. Testing the patient with bilaterally sectioned vestibular nerves, the same used in the previously mentioned experiment, showed no effect of galvanic stimulation and a total inability to sense the chair's rotation, indicating that the nonvestibular cues did not seem useful in sensing chair rotation and that an intact vestibular nerve was necessary for sensing either rotational or galvanic stimulation of the system. It is further of interest to note that there was no gross evidence of any adaptation of the vestibular system to galvanic stimulation in this type of experimental situation.

Current research is directed toward assessing the effect of galvanic vestibular stimulation on posture control, very much as outlined in the first experiment. We also will be looking at the electromyographic responses to obtained a better idea of the timing in the central nervous system of the various reflexes. We are adding the cervical proprioceptive stimuli of head turning, which should rotate the effect of the galvanic stimulus on lower limb motor control by approximately 90 degrees.

We hope by these experiments to take another step toward the building of models for postural stability. As we begin to understand the role played by various sensory inputs and motor output control, three types of clinically useful data may emerge.

The first is an improvement in diagnostic localization of lesions. Hopefully, we will be able to assess the contributions of each system to postural stability separately and thereby isolate the system that is malfunctioning in a given patient. Second, by analyzing the characteristics of the malfunction, it may be possible to provide the necessary substitutions that will allow for a more nearly normal input and output. Third, by a better understanding of how the organism itself compensates for malfunction in any one system, we may learn better the load limits within the components of the system that yet remain compatible with normal or nearly normal function. All such information can lead eventually to the production of better prosthetic and physical therapy techniques in the neurologically handicapped population. Obviously, what we have presented is only a small beginning toward this rather large undertaking. We are convinced, however, that only the combination of model building and biological experiment can provide the framework for understanding the massive complexity of the problem of static and dynamic postural control.

REFERENCE

1. Young, L. R. The current status of vestibular system models, *Automatica,* vol. 5, pp. 369-383, Pergamon Press, 1969.

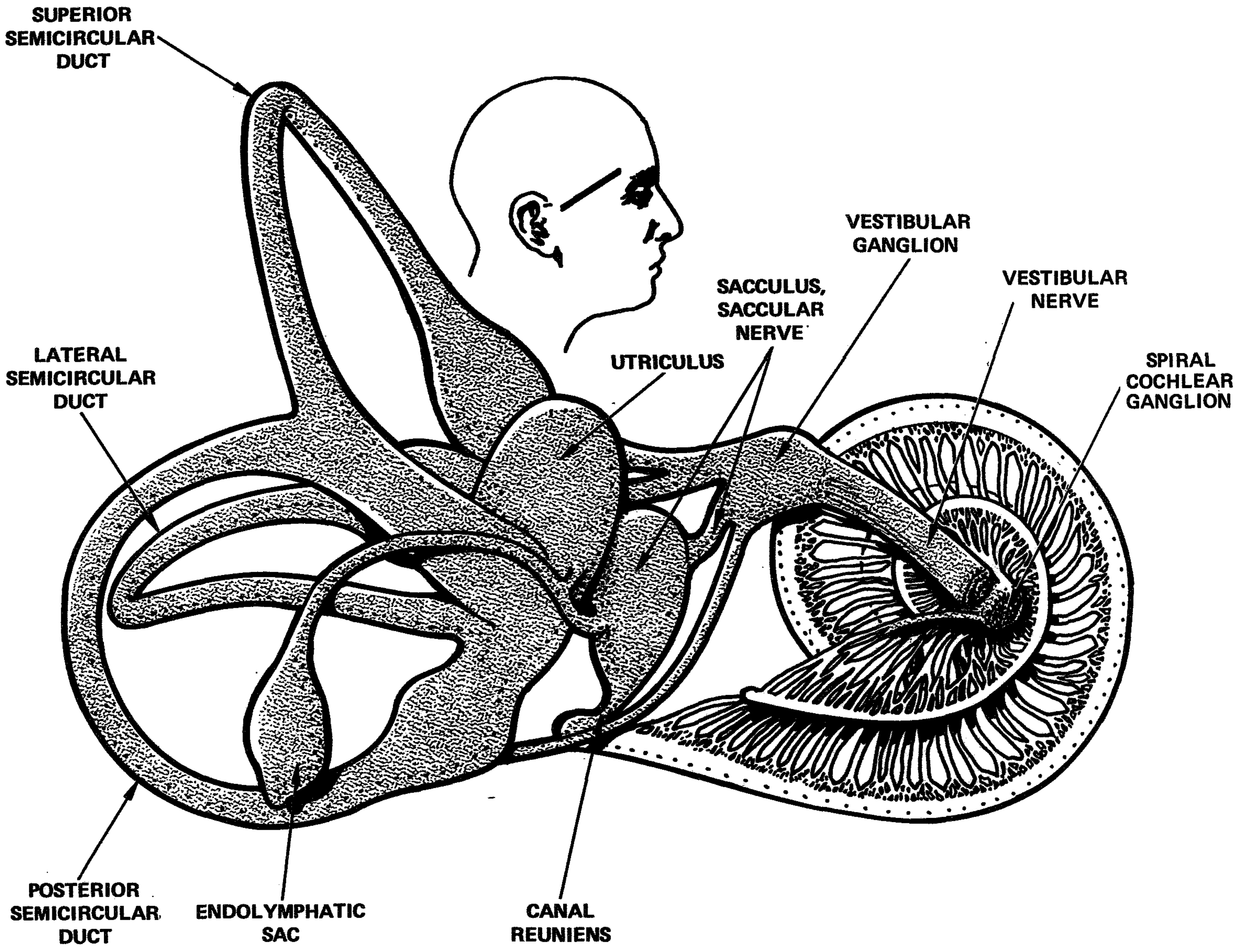

Fig. 17-1.– The human vestibular apparatus.

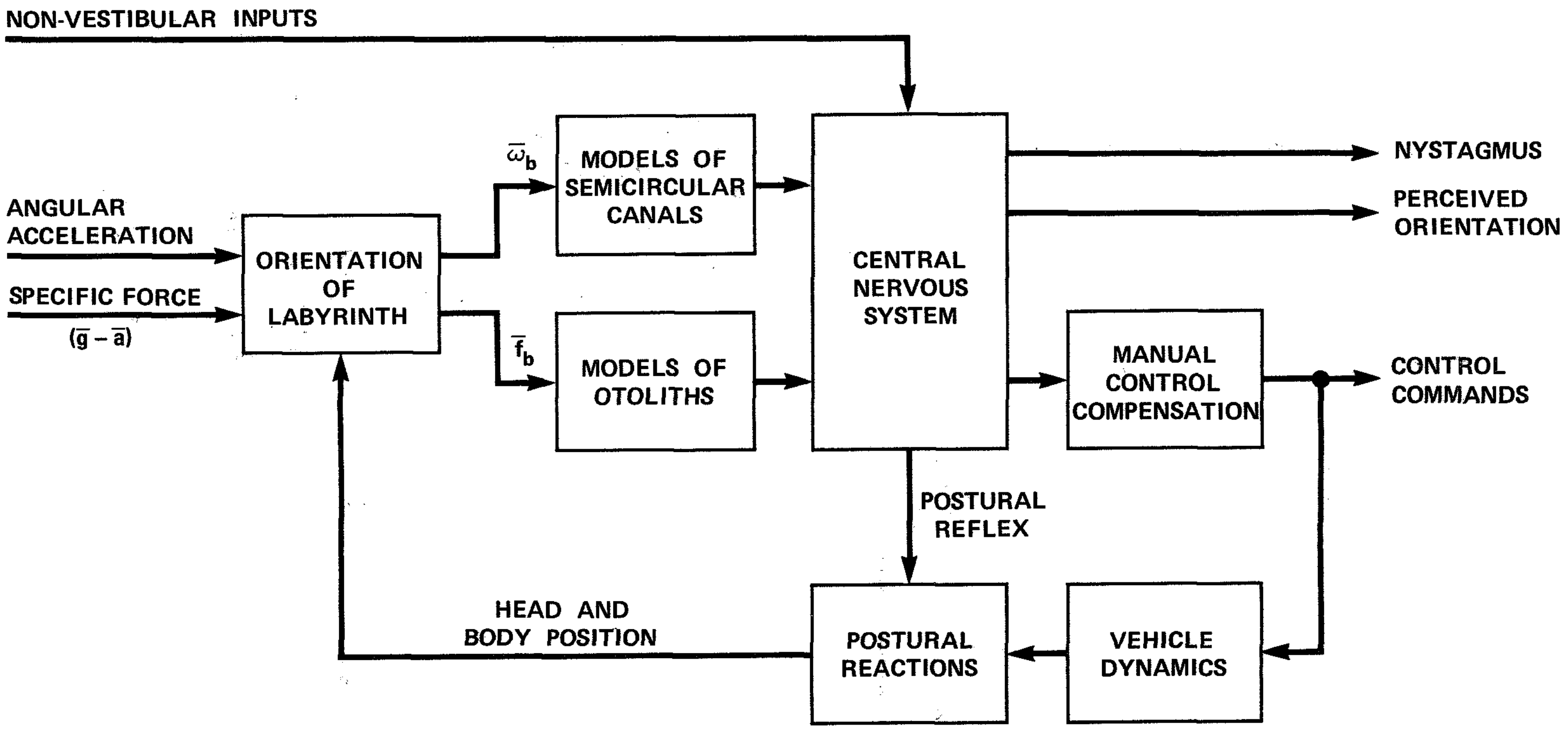

Fig. 17-2.– The control engineer's view vestibular apparatus as an input-output system.

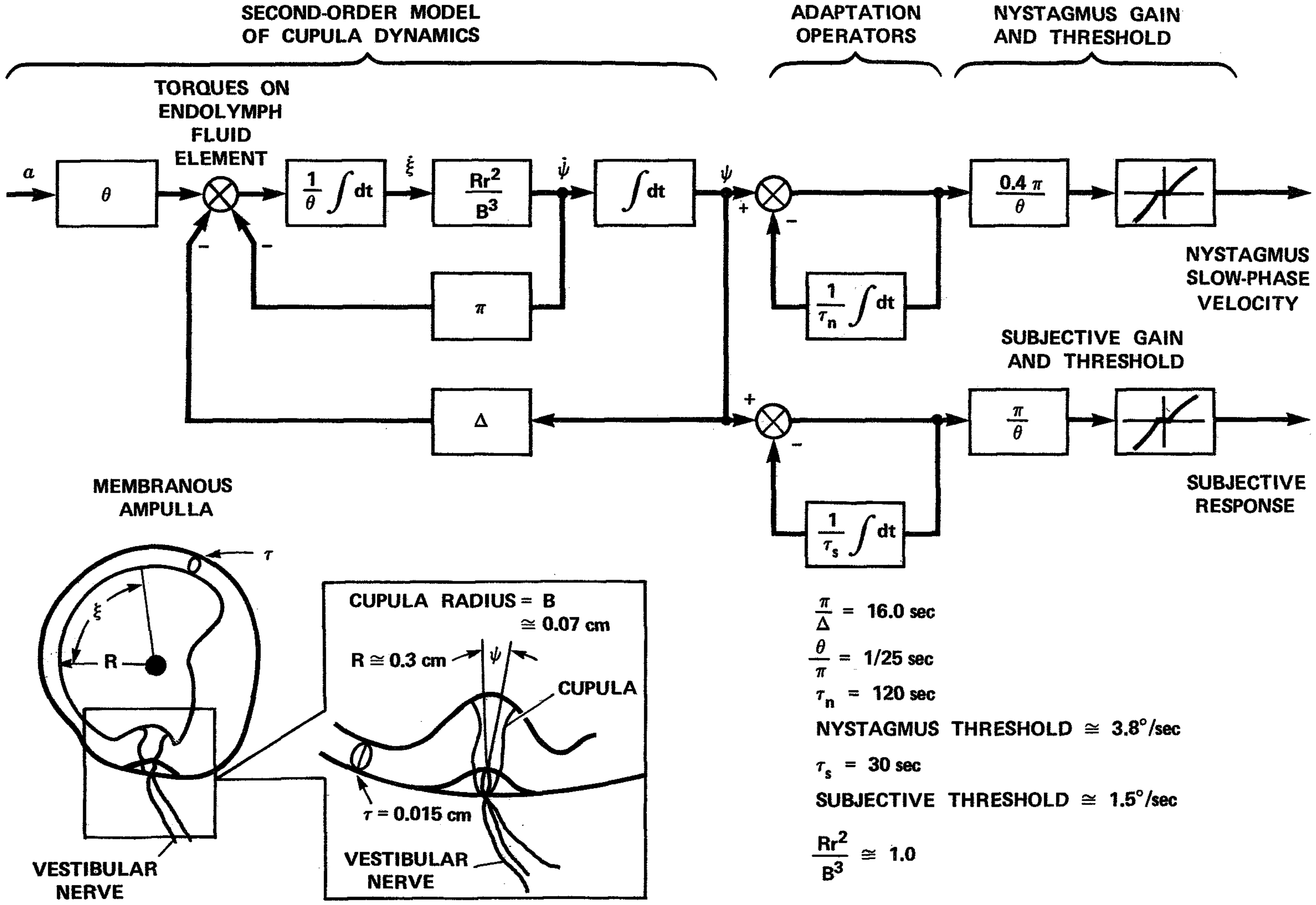

Fig. 17-3.– Mathematical model for the operation of the semicircular canals.

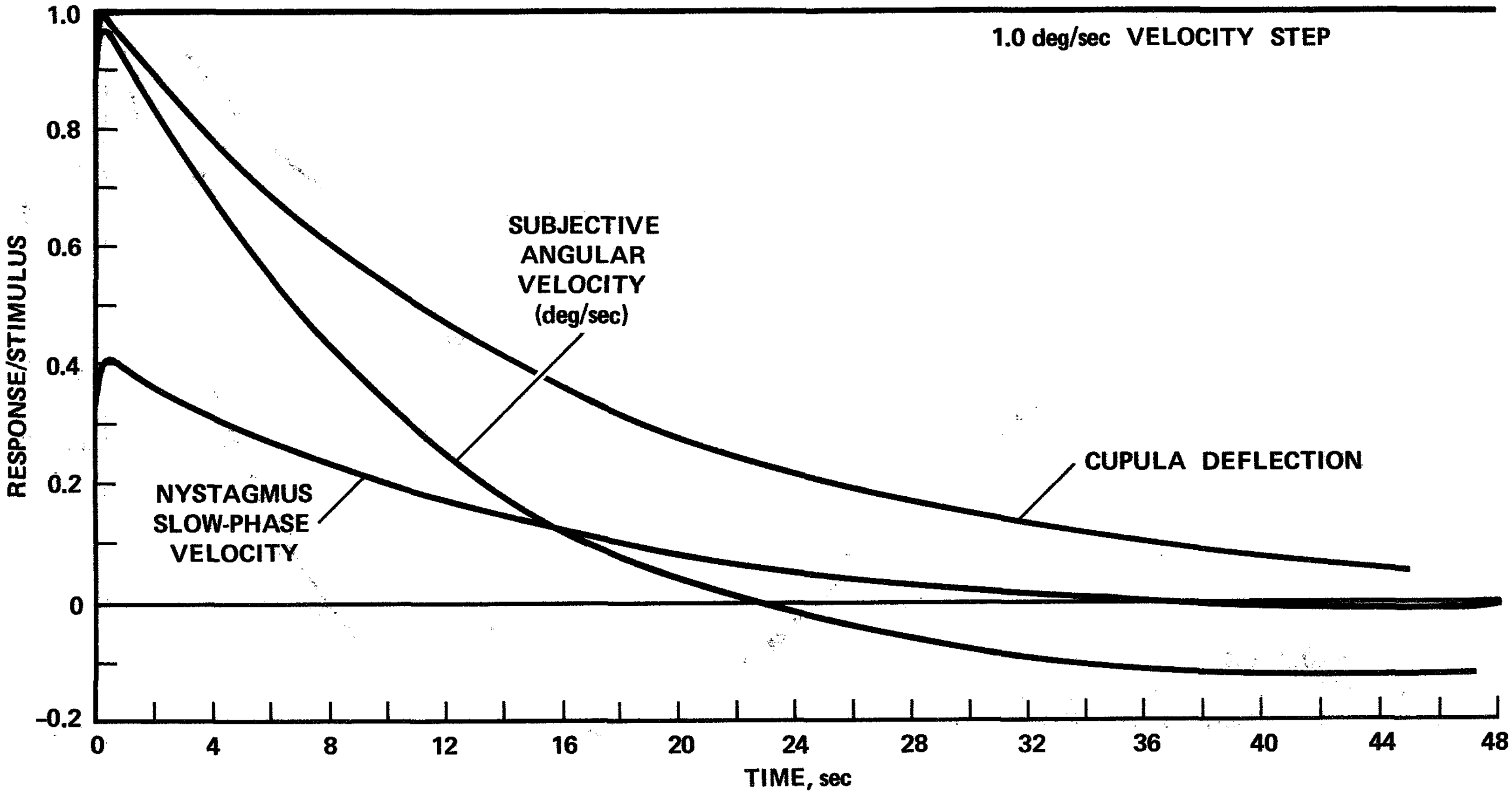

Fig. 17-4.– Velocity step response of MIT semicircular canal linearized model.

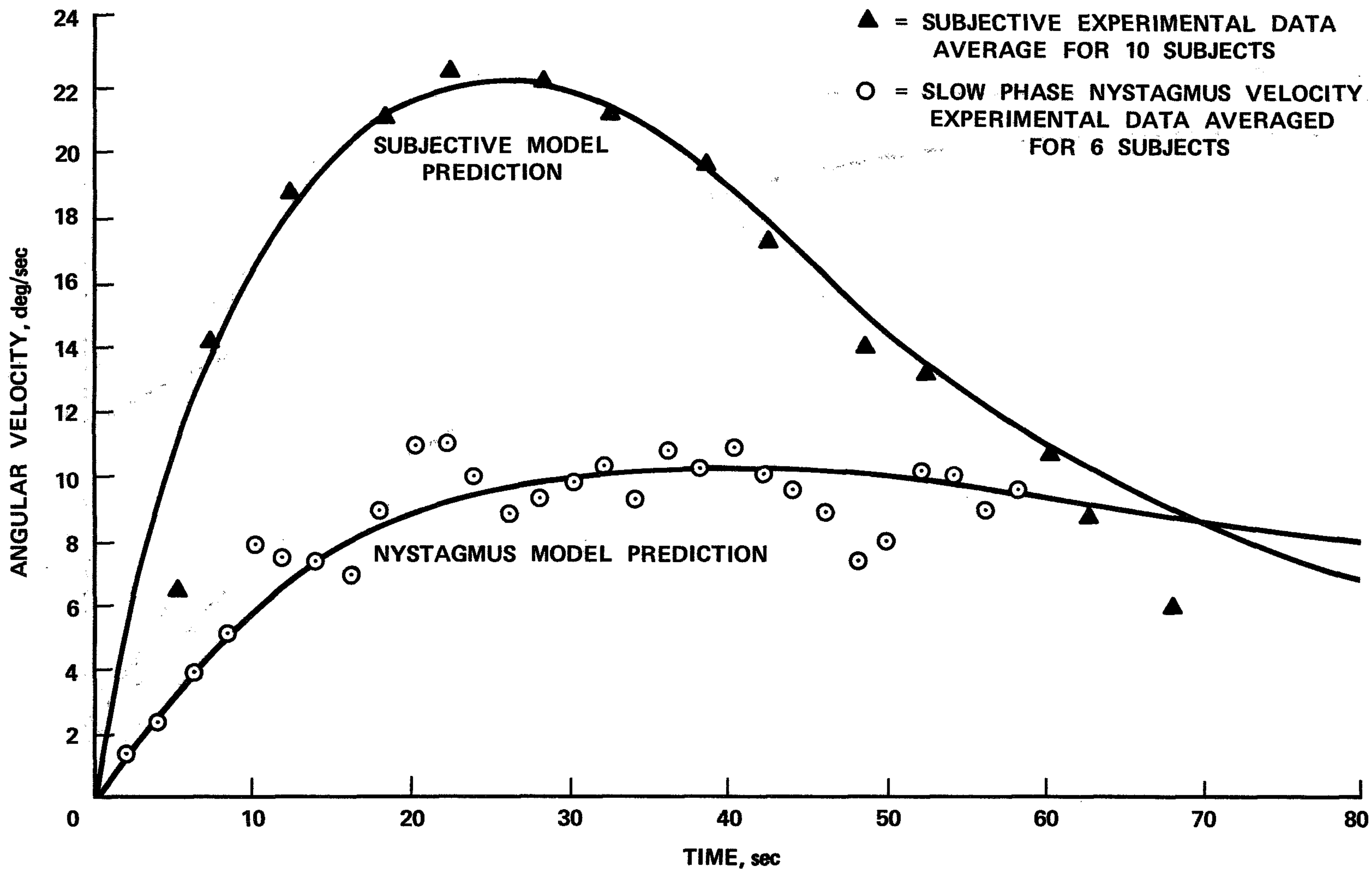

Fig. 17-5.– Comparison of adaptation model for vestibular response with experiments for an angular acceleration step (1.5 deg/sec^2).

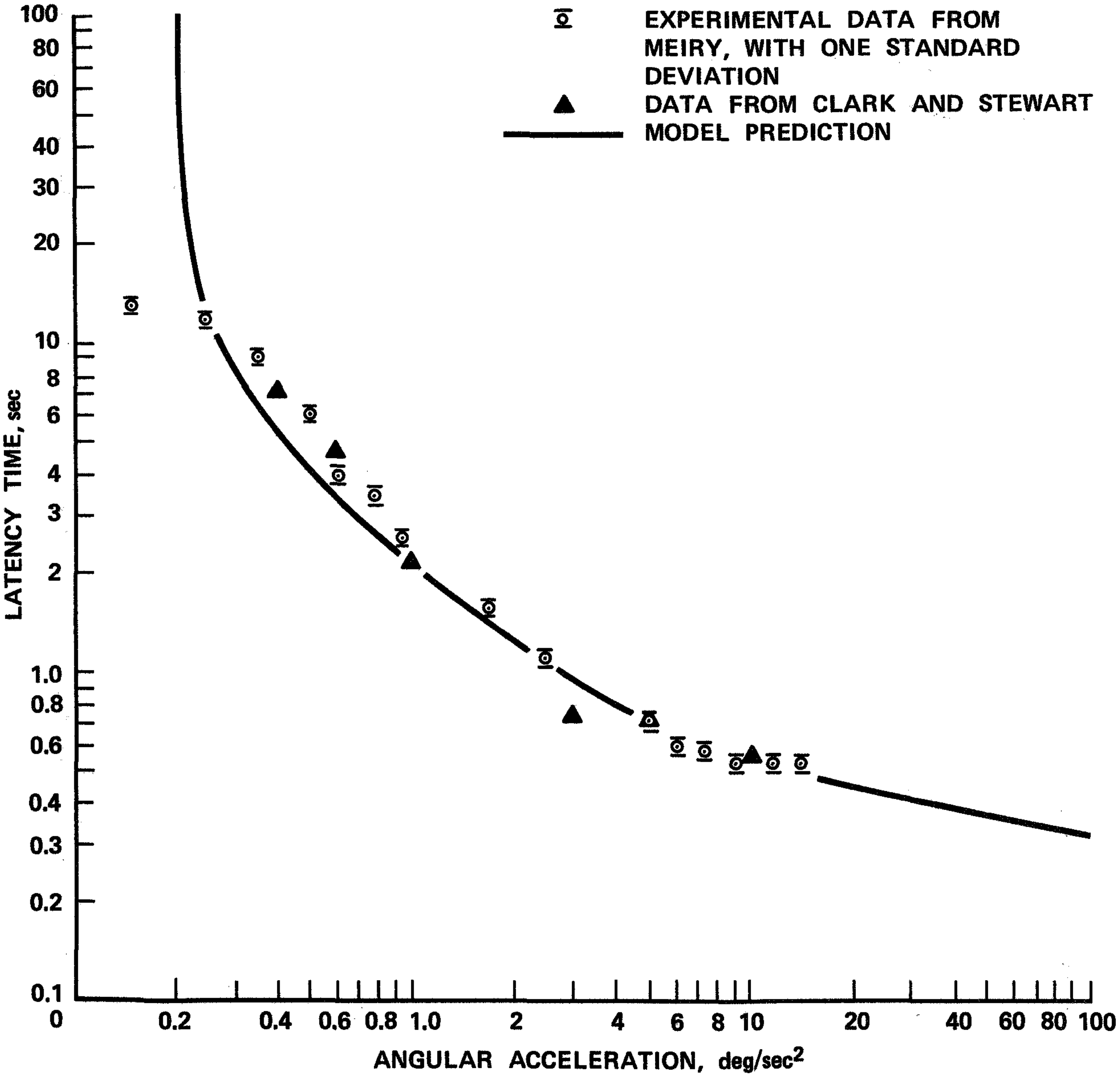

Fig. 17-6.– Adaptation model of semicircular canals.

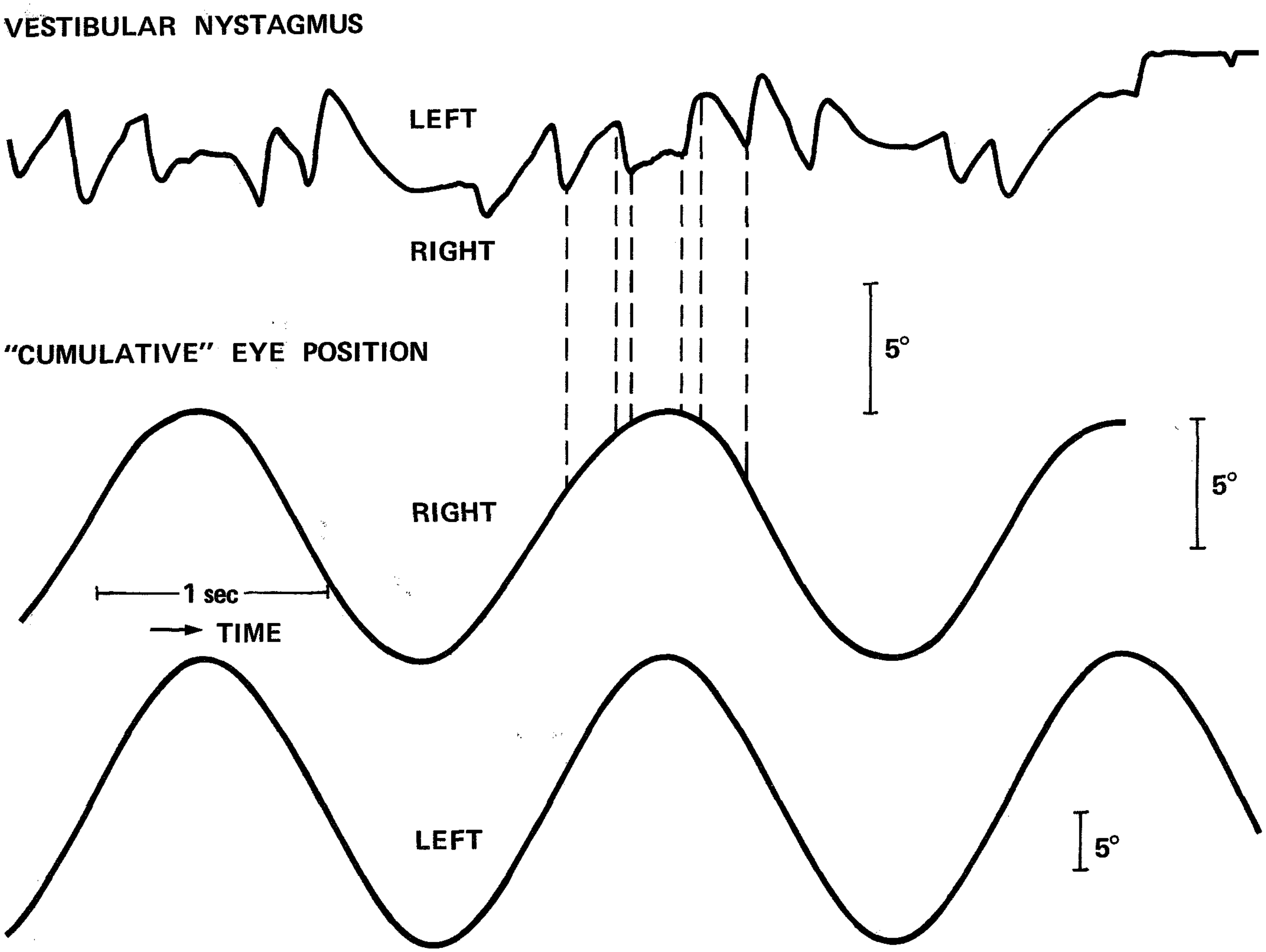

Fig. 17-7.— Vestibular mystagmus and "cumulative" eye position during oscillation about a vertical axis.

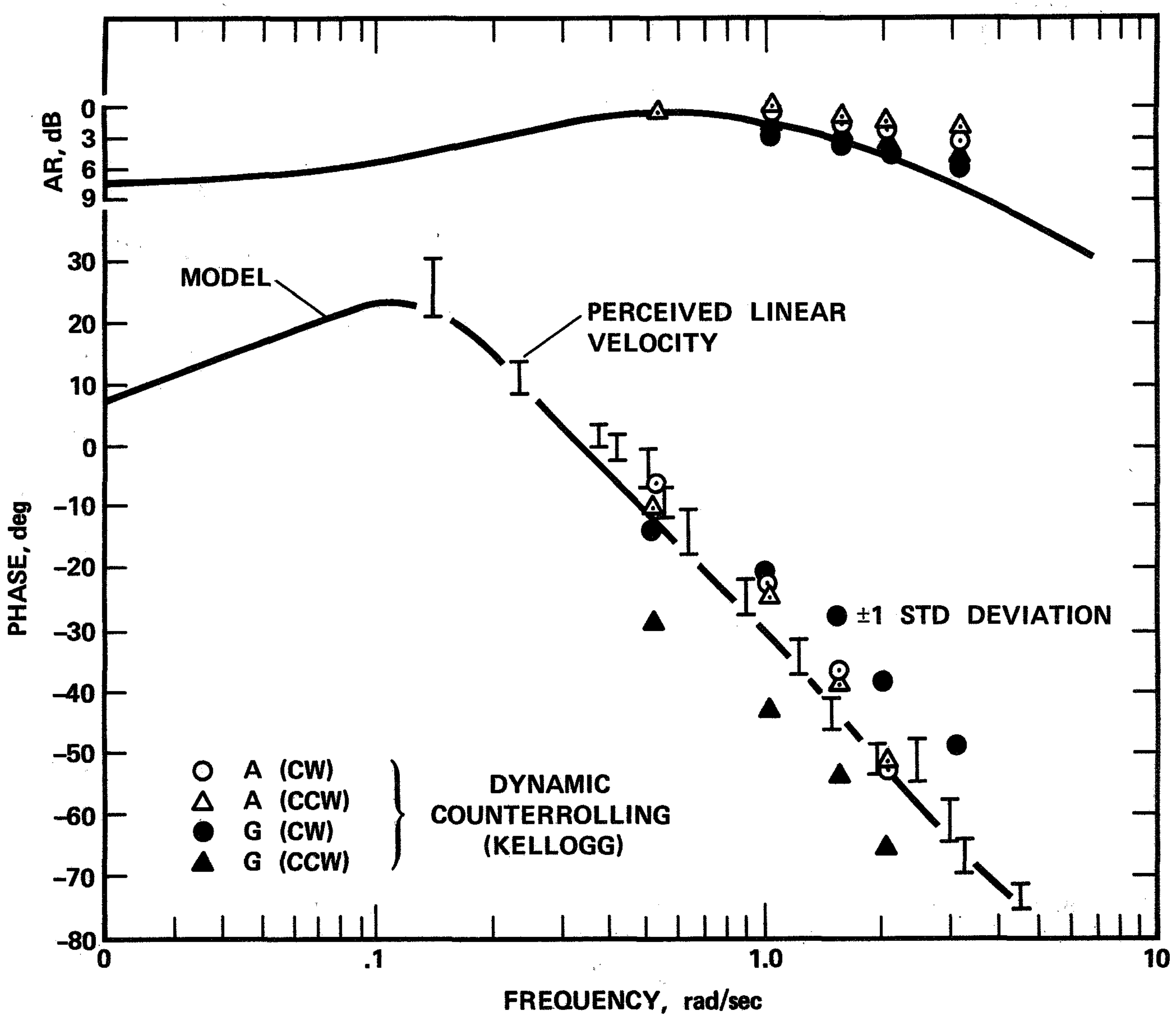

Fig. 17-8.– Perceived linear velocity frequency response.

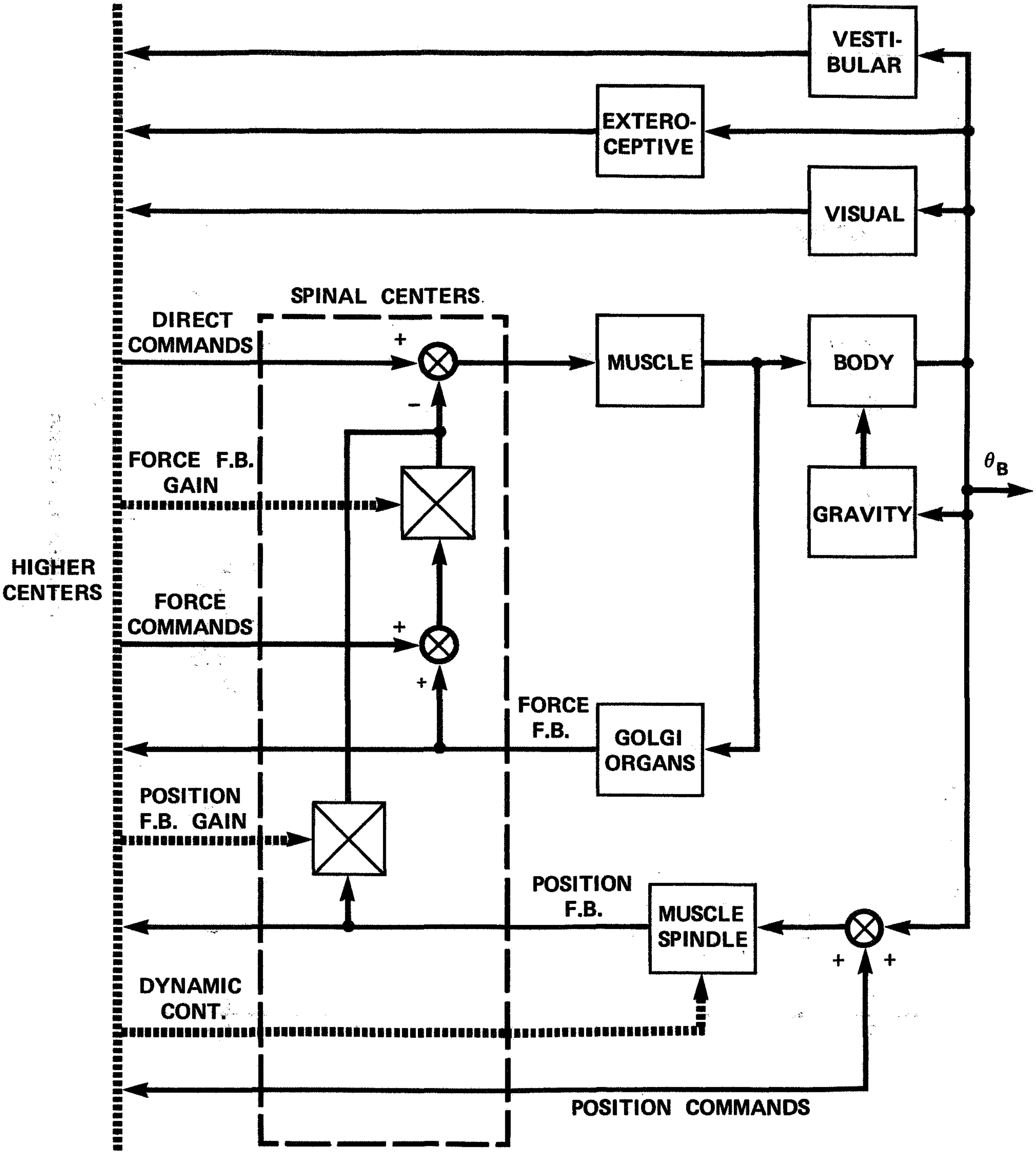

Fig. 17-9.– Diagram of system study of feedback loops in postural control.

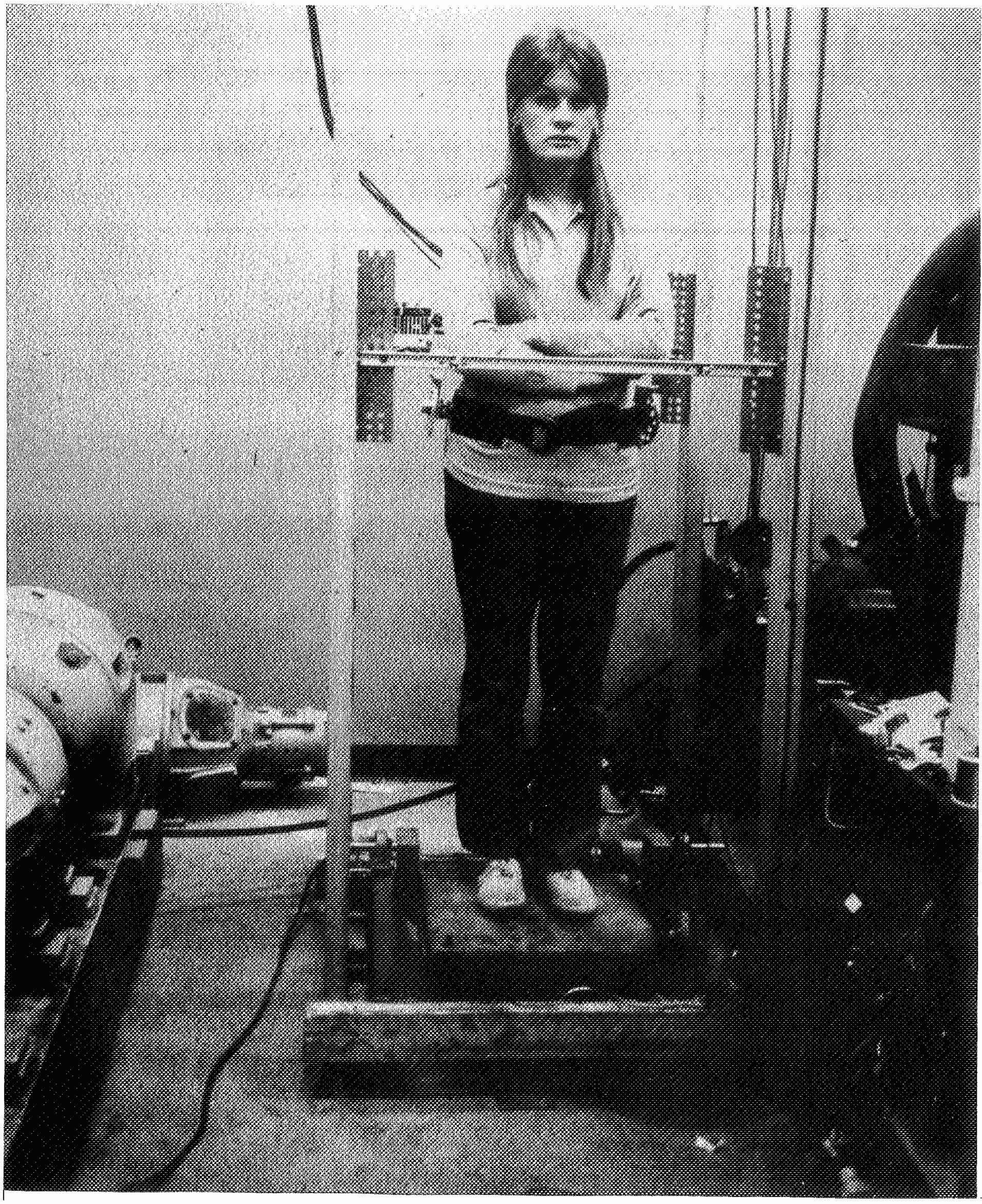

Fig. 17-10.– Apparatus for testing postural stability.

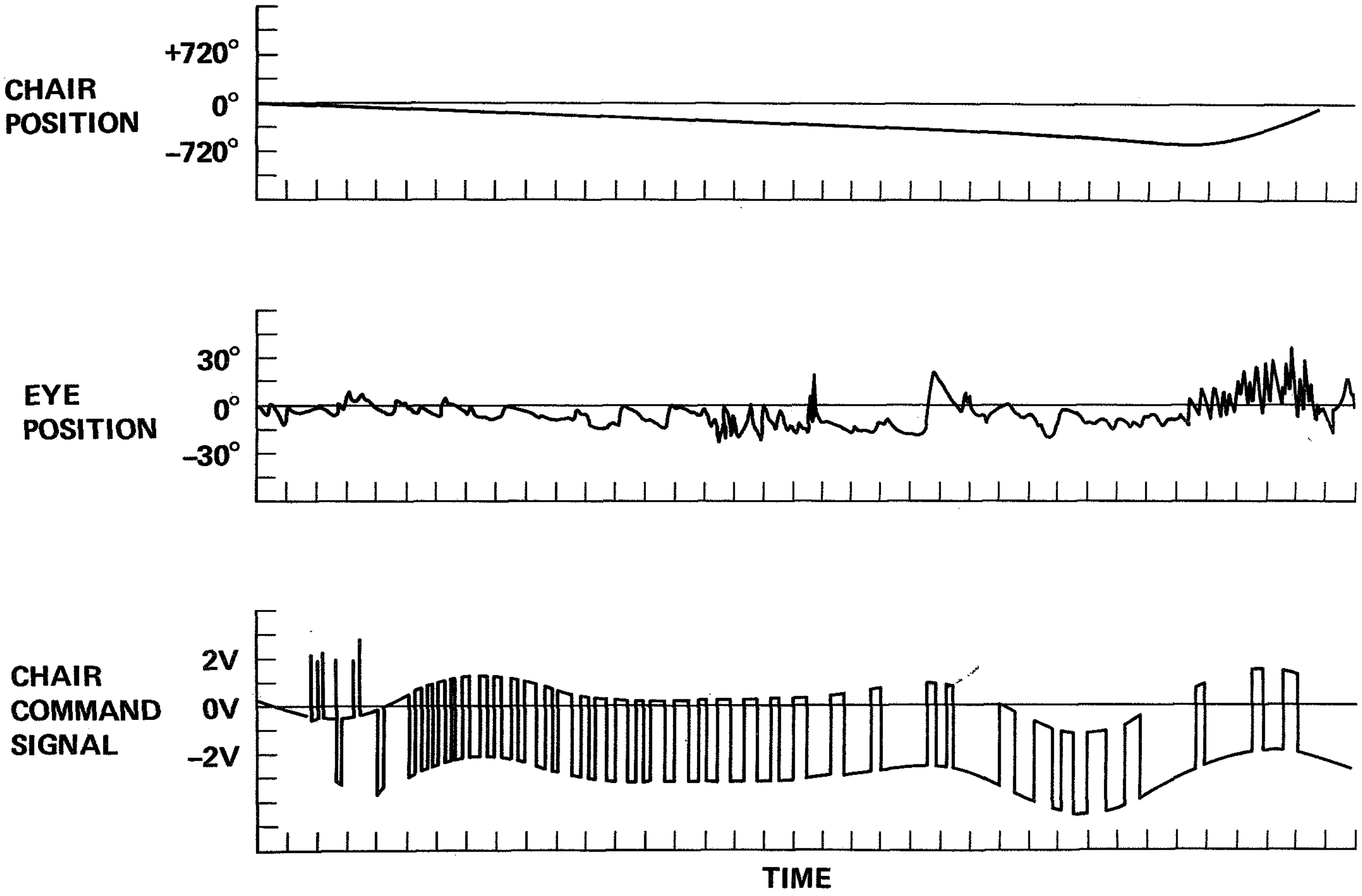

Fig. 17:11.– Typical experimental data (galvanic stimulus: unipolar left anode; 1.6 ma).

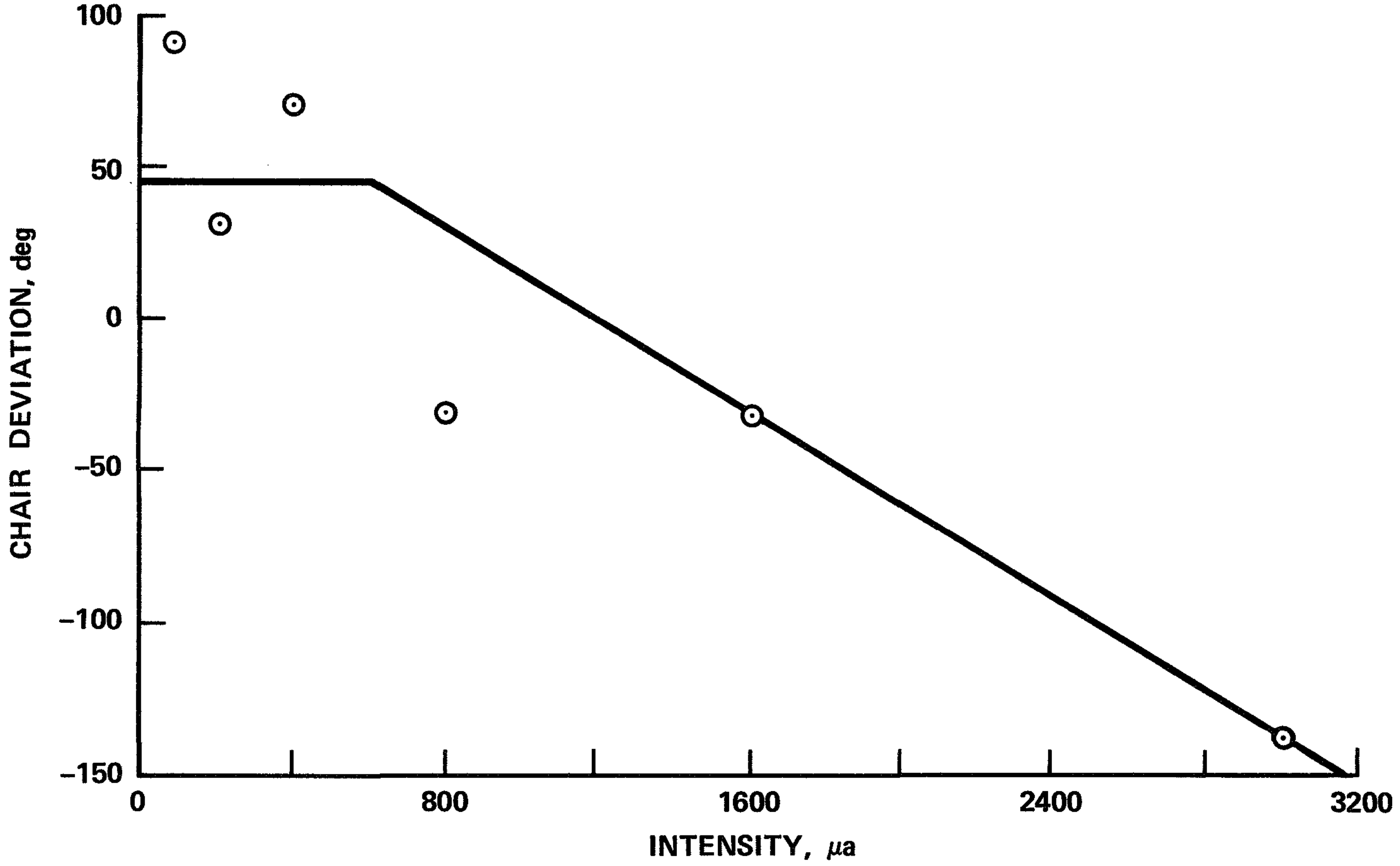

Fig. 17-12.— Chair deviation vs. galvanic stimulus intensity.

Chapter 18

MANUAL CONTROL THEORY AND APPLICATIONS

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As noted in earlier chapters, there is a need for more objective measures of performance in the neurologically handicapped. In some cases, these objective measures are needed as diagnostic aids in sorting out the degree of involvement of a specific neurological disorder. There also is a need for a rapid, sensitive, objective means for evaluating the effects of various therapies, as well as the effectiveness of hardware design in rehabilitation devices.

The first section of this chapter comprises a brief description of what we mean by control theory, including manual control theory, and a review of some previous physiological and neurological applications of control theory and associated engineering concepts. The discussion includes a specially tailored battery of critical control tasks that are being developed to monitor astronaut performance in long-term orbital flight.

In the second major section of the chapter, Repa discusses the application of these concepts and tasks to patients with various neurological disorders.

CONTROL THEORY

Figure 18-1 is a general block diagram of a feedback control system, and it consists of two major blocks, the controller and the controlled system. This kind of a feedback system is in common use in spacecraft and aircraft flight control systems. In the machine-machine aircraft system situation, for example, the control would be an autopilot, and the controlled system would be the aircraft. In operation, you have a command signal that could either be fixed, set at zero, or at a constant level of reference like a thermostat; or it could comprise varying signals, which the controller would control in an attempt to minimize any errors between the output signal of the total system and the desired command signal.

This particular analysis has proved to be a very powerful tool in technological design and in the analysis of technological control systems. The design and analysis of these systems is relatively simple because where these are all machine elements, they can be described analytically or in mathematical terms, and one can then design a system in a very straightforward manner. The performance of the total system also can be predicted and then measured on the actual system.

The man-machine feedback control system shown in Figure 18-2 is a little more complicated than the previous one, but it has essentially the same elements, with command or forcing functions controlled by the human operator, a pilot in this case, by means of some visual displays. Note also the controlled element, which could be an aircraft, a spacecraft, or a prosthetic device. The problem here, when you want to develop an analytical framework, is to describe the human operator, in particular, how he behaves under a variety of task situations. Where the task difficulty varies in aircraft systems, for example, in different phases of flight or in emergency situations, the pilot must develop control strategies to cope with these varying task demands, and we must be able to model the pilot under these conditions.

So when we are talking about control theory, we are really talking about the ability to mathematically model all elements in a closed feedback control system and model these with mathematical descriptors. In connection with man-machine systems, fortunately over the past two decades or more, a series of elegant experiments have been performed by various groups – industrial, government, and university laboratories – which have resulted in a large body of knowledge on manual control theory related to the behavior of the human operator or the pilot in various control task situations.

The body of knowledge and the techniques of manual control theory have been used in a number of technological control system design and analysis problems, such as the design of aircraft and spacecraft guidance and control display systems, the monitoring and evaluation of pilot or astronaut performance, and the prediction of pilot-vehicle performance for new aircraft designs.

In addition to man-machine control systems applications, there have been increasing applications of feedback control theory and of other concepts related to the use of information theory, and computer technology, to describe biological or physiological subsystem behavior. These include: the neuromuscular system, pupillary control, tactile control, blood pressure regulation, eye tracking control, regulation of body temperature, and postural control.

Very elegant models of the neuromuscular system have been developed by a number of people including McRuer (Chap. 19). A sophisticated control theory model of the pupillary light reflex control system was developed years ago by Larry Stark (presently at U. C. Berkeley). Considerable laboratory work by Bliss and others has been devoted to the development of a control theory model of the tactile control system.

Urquhart at the University of Pittsburgh has developed a description of the blood pressure regulation system, specifically that related to the baroceptor reflexes. And, of course, Larry Young developed an eye tracking control system model years ago. Jim Hardy's research at the John Pierce Foundation, and some more recent work done in our own thermophysiology laboratory has improved the description of the fairly complicated body temperature control system. The postural control system and vestibular system descriptions are discussed by Young and Weiss in Chapter 17.

In the general field of applying control theory to physiological control systems, an excellent text is that by Milhorn of University of Mississippi Medical Center. It provides some of the basic elements of control theory and gives a series of applications of these engineering tools to physiological systems.

Stark has recently written a book on neurological control systems, which includes a number of very interesting examples of neurological control systems for normal as well as neurologically handicapped people. (See list of references.)

As noted by Wyatt (Chap. 2), the aerospace program is primarily concerned with the performance of normal people, astronauts and pilots, in unusual environments. On the other side of the coin is the need to provide objective measures of performance for patients with various neurological disorders. In addition to the use of objective measures as diagnostic aids and in the evaluation of therapeutic measures, noted earlier, an important potential area for the application of the engineering principles and theories discussed is in the design of improved limb movement devices. As noted by Lee Arnold (Chap. 1), we should be able to solve the spastic or undesirable motion problems of the neurologically afflicted in the same way that we handle problems of stabilizing undesirable aircraft motions, through the design of flight control systems.

Figure 18-3 is an example, from Stark, of the possible use of control theory and analysis for diagnostic situations. Stark had a group of normal subjects, as well as patients with varying degrees (mild and moderate) of Parkinson's syndrome, perform a tracking task of the sort we have used in man-machine studies over the years. The task was a closed loop control task where the subjects were controlling a pointer with one hand. They had to stabilize the pointer to maintain zero error around some null position in the presence of some disturbing (command) inputs to the pointer. Stark obtained frequency response characteristics, which are frequently used for evaluating technological systems, for both normal subjects and patients. The frequency-response gain results (Fig. 18-3) indicate a remarkable reduction in the bandwidth or the ability of the patients with varying degrees of Parkinson's syndrome to cope with high frequency command inputs. Frequency response phase data (not shown) indicated significantly increased lag in the responses of patients relative to those of normals.

The critical task battery is provided by three basic elements – a control stick manipulator, a visual display, and a controlled element computer (Fig. 18-4). We provide task variation through either changes in disturbance inputs or unstable controlled element to make the line move on the scope. The task is to keep that line centered in the presence of either disturbance inputs or an unstable controlled element.

The controlled element computer sets the desired task and is used as noted to control the difficulty of the task. A describing function analyzer is used to determine the human operator's frequency response, both in gain and in phase, at the end of each tracking run.

Figure 18-5 is a closed loop block diagram again. Note that in this case the command input is zero, and we increase the difficulty of the task by varying the rate of divergence of the controlled element. As that number λ increases, as shown to the right, the task becomes more difficult, and at some point control is lost. This task is roughly analogous to balancing a pointer on one's finger. As the pointer is increasingly telescoped to smaller and smaller lengths, it becomes increasingly difficult to control.

A number of other tasks in this critical task battery are of interest in evaluating astronaut performance in orbital flight. The so-called "first-order critical task" was singled out because it was one of several used by Repa, Albers, and Tourtellotte. Repa discusses some of their results in clinical trials in the next section.

APPLICATIONS OF TRACKING TO THE EVALUATION OF MOTOR DISABILITIES

The potential of tracking tasks for use in clinical applications has been recognized for many years. Tracking tasks are excellent for systematically studying the sensory-motor performance of normal subjects as well as that of patients suffering from neurological disorders. Their chief value in a clinical setting comes from the information they provide for detecting and documenting changes in a patient's condition. The ability to evaluate changes in performance resulting from disease progression in controlled clinical trials is essential in establishing effective treatment programs. While clinicians are usually able to classify a patient's motor disability into gross categories such as mild, moderate, and severe, they often have difficulty in detecting small but significant changes in neurological function over time. Tracking tasks can help by providing a more objective and quantitative look at motor function.

Performance in a tracking task can be represented by graphic displays of spatial-temporal movement patterns in conjunction with records of the input signal as well as by quantitative indices based on different aspects of limb movements and tracking errors. At the University of Michigan's Neurology Research Laboratory, both these approaches have been used with patients suffering from diseases of the nervous system. Phase plane diagrams – plots of velocity versus position – have been used to display the step responses of patients with multiple sclerosis and to contrast these responses with those of subjects with other neurological conditions. In addition, quantitative indices of tracking performance have been used in a drug trial designed to compare the efficacy of amantadine to that of a placebo in treating Parkinsonian patients already receiving an optimal dose of L–DOPA.

To be effective in a clinical environment, the tracking tasks had to require the shortest run lengths and the fewest trials possible to establish stable patient performance levels. Extensive training time was a luxury that simply could not be afforded. All tests and measures had to allow the use of on-line data reduction schemes. The battery of tracking tests that was used included step tracking, random tracking, and critical tracking (Fig. 18-6). The tests were kept as simple, yet as comprehensive and challenging, as possible. A position control stick with negligible dynamics and a large range of movement was used to keep response limitations imposed by the equipment to a minimum. An oversize display screen with large vertical lines for target and follower helped to reduce the effects of any visual problems the patients had.

While quantitative indices of tracking performance are useful in evaluating the effects of different types of therapy, spatial-temporal response records provide a more complete source of information on tracking performance. Such records preserve the interesting movement characteristics and often provide a basis for hypotheses that further the understanding of motor performance. Furthermore, inspection of graphic records often provides the rationale for choosing among different possible quantitative indices for describing the disorders.

Phase plane diagrams were used to display the step responses of patients with various movement disorders, with special interest directed to multiple sclerosis patients. Figure 18-7 illustrates typical step response patterns for four subjects with widely varying neurological conditions. The response patterns can be summarized as follows:

1. Young adult normal: The step response is rapid and precise and exhibits a single, small overshoot.

2. Multiple sclerosis patient with moderate to severe intention tremor: Classical intention tremor, which appears only during active movements, is clearly demonstrated. No tremor is present at rest or during the early part of the movement; but as the target is approached, oscillations appear and then persist for several seconds after the target region has been reached. The step response is somewhat violent, and the patient has considerable difficulty in settling on the exact target position.

3. Parkinsonian patient with severe resting tremor: A classical form of resting tremor is shown. The tremor becomes manifest at rest and ceases during voluntary movement. There is a characteristic delay of several seconds between the stoppage of the movement and the reappearance of tremor. The tremor begins with small amplitude oscillations and reaches its accustomed level within a few cycles.

4. Adult cerebral palsy patient with mild intention tremor and slight resting tremor: The step response is rapid and precise except for mild oscillations at the end of the movement. These oscillations settle down to a low amplitude tremor, which remains at rest.

Figure 18-8 shows families of trajectories for four normal young adult subjects. While there is considerable variability in peak velocities between subjects, intrasubject variability is low. A single, small overshoot is characteristic of most of the responses.

Families of trajectories for six multiple sclerosis patients are shown in Figure 18-9. The patients are listed according to a physician's subjective evaluation of their intention tremor, from slight to moderate-severe. The movement patterns thus vary from those that differ only slightly from normal to patterns that show violent oscillations about the target point.

The information contained in these plots can be transformed into quantitative measures. For example, the Parkinsonian study, considered later, used a movement time measure based on the time between the first large move away from zero in the velocity record and the return to zero. While movement time is a meaningful measure of step tracking performance for normals and Parkinsonian patients, inspection of the phase plane diagrams for multiple sclerosis patients suggests that additional measures are required to effectively describe their performance. The neurologist's evaluation of intention tremor is based on a subjective weighting of different aspects of the speed and accuracy of a movement toward a target, as in the finger-to-nose test. Movement time, decomposition, overshoots, and oscillations about the target all enter into his evaluation. A number of precise performance measures used by control engineers for judging the step responses of physical systems are equally appropriate for quantifying movement disorders in a tracking task. Time delay and rise time are two measures that are closely related to reaction time and movement time. More important measures, as far as intention tremor is concerned, are peak overshoot and settling time. Peak overshoot is the largest error between input and output during the transient state while settling time is the time required for the response to decrease and stay within a specified percentage of its final value. Inspection of the phase plane trajectories for multiple sclerosis patients (Fig. 18-9) strongly suggests that the neurologist is also influenced by these performance measures in making his rating and that these measures can provide a meaningful and objective characterization of patient performance.

Quantitative performance indices are particularly important in evaluating controlled therapeutic trials. The performance indices listed in Figure 18-6 were applied in a drug trial designed to compare the efficacy of L–DOPA and amantadine to that of L–DOPA and placebo in the treatment of 28 patients with Parkinson's disease. Whenever new quantitative tests for measuring neurological disorders are developed, it is of interest to examine the performance of normal subjects as well as patients on the tests. Reliabilities and learning effects are more effectively measured with normal subjects due to the possibility of large variations in patients' performance that can be justifiably attributed to their pathological condition. Ten age-matched normals were used in a test-retest study to determine reliability coefficients for the tracking measures. As shown in Table 18-1, all coefficients were found to be significant at or below the 5 percent level with the exception of movement time for a right-to-left transition, and the coefficient for this measure was just short of the cutoff point. The same group of ten normals was used to measure learning effects, as shown in Table 18-2. Although all test scores showed an improvement on the second test, none of the improvements was statistically significant.

Another important reason for using normal subjects in new tests is to establish normative performance levels. Since it is the goal of the physician to bring the performance of patients to the predisease level, it is meaningful to express patient data as a percentage of that obtained from matched normal controls. This was done for the drug study, which was based on a randomized, double-blind, crossover design. The 28 Parkinson's disease patients were randomly assigned to two groups, the first receiving L–DOPA + amantadine first and L–DOPA + placebo second, with the second group receiving just the opposite schedule (Table 18-3). Treatment groups were combined for analysis, and scores were expressed as a percentage of matched normal levels (Table 18-4). Relative to the normal subjects, patients performed worse on random tracking than on step tracking or critical tracking. Improvements were modest when amantadine was taken in addition to L–DOPA.

Table 18-1

Reliability of Tracking Test Battery Involving Ten Matched Normals with Three-Week Interval Between the First and Second Examinations.

Tracking Test	r*	$\frac{2r}{1+\lvert r \rvert}$†
Step		
Reaction time, right to left	.75 ($p \leqslant 0.05$)	.86
Reaction time, left to right	.82 ($p \leqslant 0.01$)	.90
Movement time, right to left	.60	.75
Movement time, left to right	.67 ($p \leqslant 0.05$)	.80
Random		
Integral of absolute error	.91 ($p \leqslant 0.001$)	.95
Critical		
Reciprocal of critical root	.96 ($p \leqslant 0.001$)	.98

*Pearson product moment correlation coefficient
†Spearman-Brown split-half correlation formula

Table 18-2

Learning in Tracking Test Battery Involving Ten Matched Normals with a Three-Week Interval Between the First and Second Examinations.

Tracking Test	Exam I Mean	Exam I SD	Exam II Mean	Exam II SD	Difference	% Change	t–Difference	t–% Change
Step (in msec)								
Reaction time, right to left	308	44	305	43	−3	−.3	.27	.10
Reaction time, left to right	297	37	297	51	0	−.2	.00	.07
Movement time, right to left	510	80	493	106	−17	−2.7	.62	.53
Movement time, left to right	596	109	530	116	−66	−10.5	2.29	2.41 ($p \leqslant 0.05$)
Random (in cm-sec/sec)								
Integral of absolute error	1.93	.54	1.89	.52	−.04	−1.4	.68	.35
Critical (in msec)								
Reciprocal of critical root	371	56	361	61	−10	−2.6	1.77	1.79

$$\text{*Percent Change} = \frac{1}{10}\sum_{i=1}^{10} \frac{\text{Score } 2_i - \text{Score } 1_i}{\text{Score } 1_i} \times 100$$

Table 18-3

Experimental Paradigm.

Group	No. of Patients	Medication Taken During Week 1 – 3	Medication Taken During Week 4 – 6
1	14	L–D+A	L–D+P
2	14	L–D+P	L–D+A

L – D = L–DOPA A = amantadine P = placebo

Table 18-4

Performance of Patients in the Tracking Test Battery Expressed as a Percentage of Matched Adult Normal Function.

Tracking Test	Matched Adult Normal Function Mean ± 2SD	Patients on Placebo %	Patients on Placebo SD	Patients on Drugs %	Patients on Drugs SD
Step (in msec)					
Reaction time, right to left	303 ± 78	83	19	90	22
Reaction time, left to right	294 ± 67	83	17	86	18
Movement time, right to left	489 ± 220	78	22	80	20
Movement time, left to right	568 ± 234	76	22	84	23
Random (msec)					
Integral of absolute error	1.89 ± 1.16	61	23	65	17
Critical (in cm-sec/sec)					
Reciprocal of critical root	362 ± 128	78	17	81	18

Based on other tests administered in the drug trial (Walker et al., 1971b), the effect of adding amantadine to L–DOPA was found to be beneficial but weak. The tracking performance measures all showed improvements favoring the L–DOPA + amantadine treatment group (Table 18-5). The critical task measure and left-to-right movement time showed improvements significant at the 5 percent level. Changes in random tracking scores and right-to-left reaction time scores were 10 percent or more, but large variations in scores among patients prevented these changes from being statistically significant.

Table 18-5

Results of Tracking Test Battery Involving 28 Parkinson Patients: Comparison Between L–DOPA + Placebo and L–DOPA + Amantadine Treatment Groups.

Tracking Test	L–DOPA+Amantadine		L–DOPA+Placebo		Difference	% Change	t-Difference	t-% Change
	Mean	SD	Mean	SD				
Step (in msec)								
Reaction time, right to left	359	91	385	102	27	10	1.61	2.32 ($p \leqslant 0.05$)
Reaction time, left to right	358	84	368	81	10	4	.75	1.32
Movement time, right to left	642	145	679	215	4	7	1.18	1.46
Movement time, left to right	717	191	820	289	10	16	2.32*	2.89 ($p \leqslant 0.01$)
Random (in cm-sec/sec)								
Integral of absolute error	3.04	.74	3.36	1.35	.32	11	1.42	1.66
Critical (in msec)								
Reciprocal of critical root	463	96	486	110	22	5	2.23*	2.58 ($p \leqslant 0.05$)

$$\text{*Percent change} = \frac{1}{28} \sum_{i=1}^{28} \frac{\text{Score } 2_i - \text{Score } 1_i}{\text{Score } 1_i}$$

A number of criteria have been established for selecting tests for use in quantitatively evaluating neurological function (Table 18-6). The direct application of tracking tests to a clinical trial has shown that they are indeed capable of satisfying these criteria. While tracking tests are not meant as a substitute for sound clinical judgment, they can provide the medical investigator with information that is often impossible to obtain from observation alone, particularly in detecting and documenting changes in a patient's condition over time.

Table 18-6

Criteria For Test Selection.

Criteria Related to the Neurological Function Tested

The function must relate meaningfully to the status of the subject's nervous system.

Criteria Related to the Instrument

1. The instrument must be small and capable of being used in a small area.
2. Initial, operating, and maintenance costs of the instrument must not be prohibitive.

Criteria Related to the Test Data

1. The data must be truly quantitative – at least of interval strength.
2. The data must be objective – reliable.
3. The data must be sensitive enough to detect changes in the neurological function being evaluated.

Criteria Related to the Subject

1. The "supernormal" healthy young adult should be challenged by the test, and yet at the same time the test should not be beyond the ability of the patient.
2. The subject should be reasonably interested and motivated by the test.
3. Learning effects should be at a minimum.
4. The subject must not be so fatigued by the test as to prohibit the completion of succeeding tests in the battery.
5. The idea of the test must be simple enough to be easily communicated to the subject.

Criteria Related to the Examiner

A trained physical therapist must be capable of administering the test.

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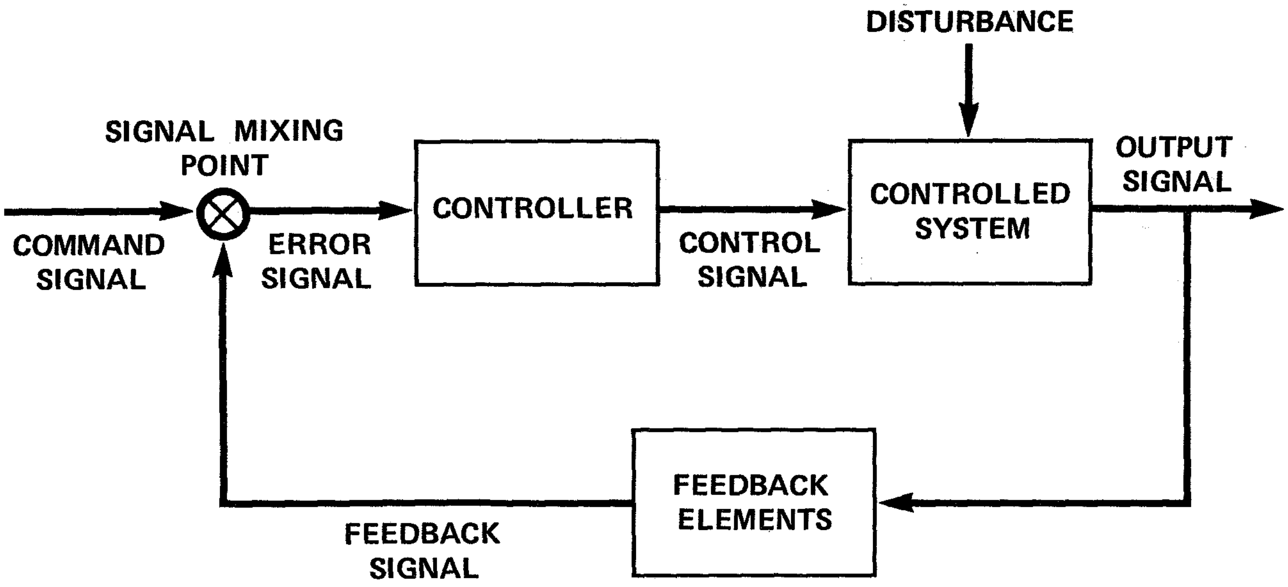
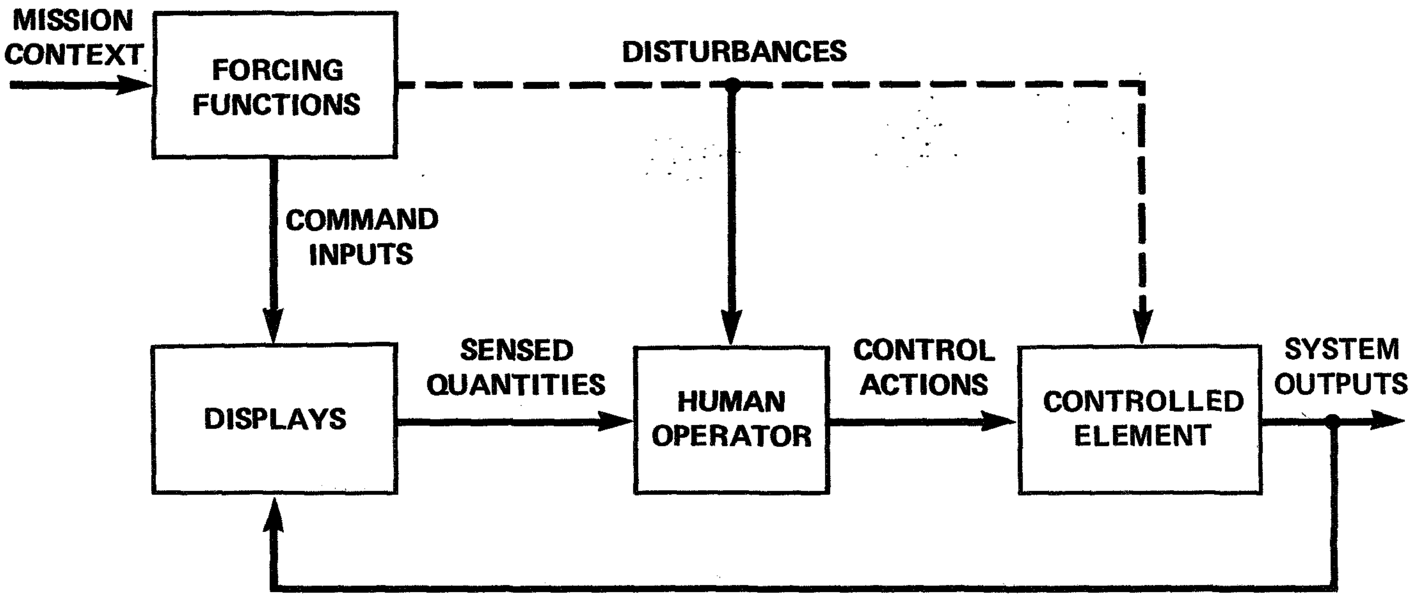


Fig. 18-1.– Generalized feedback control system.



- TASKS CONSIDERED REQUIRE THE OPERATOR TO ACT AS A PRECISE, ADAPTIVE, SENSORY-MOTOR LINK IN A CLOSED-LOOP SYSTEM

- HUMAN BEHAVIOR IN THESE TASKS DEPENDS ON MANY VARIABLES: TASK, ENVIRONMENTAL, OPERATOR-CENTERED, AND PROCEDURAL

- SYSTEM OPERATION IS CLOSED-LOOP, SO HUMAN DYNAMIC BEHAVIOR IS QUANTIFIED IN CONTROL TERMS, SUCH AS TIME DELAY, EQUALIZATION, AND OPERATOR-INJECTED NOISE (REMNANT)

Fig. 18-2.– Man/machine feedback control system.

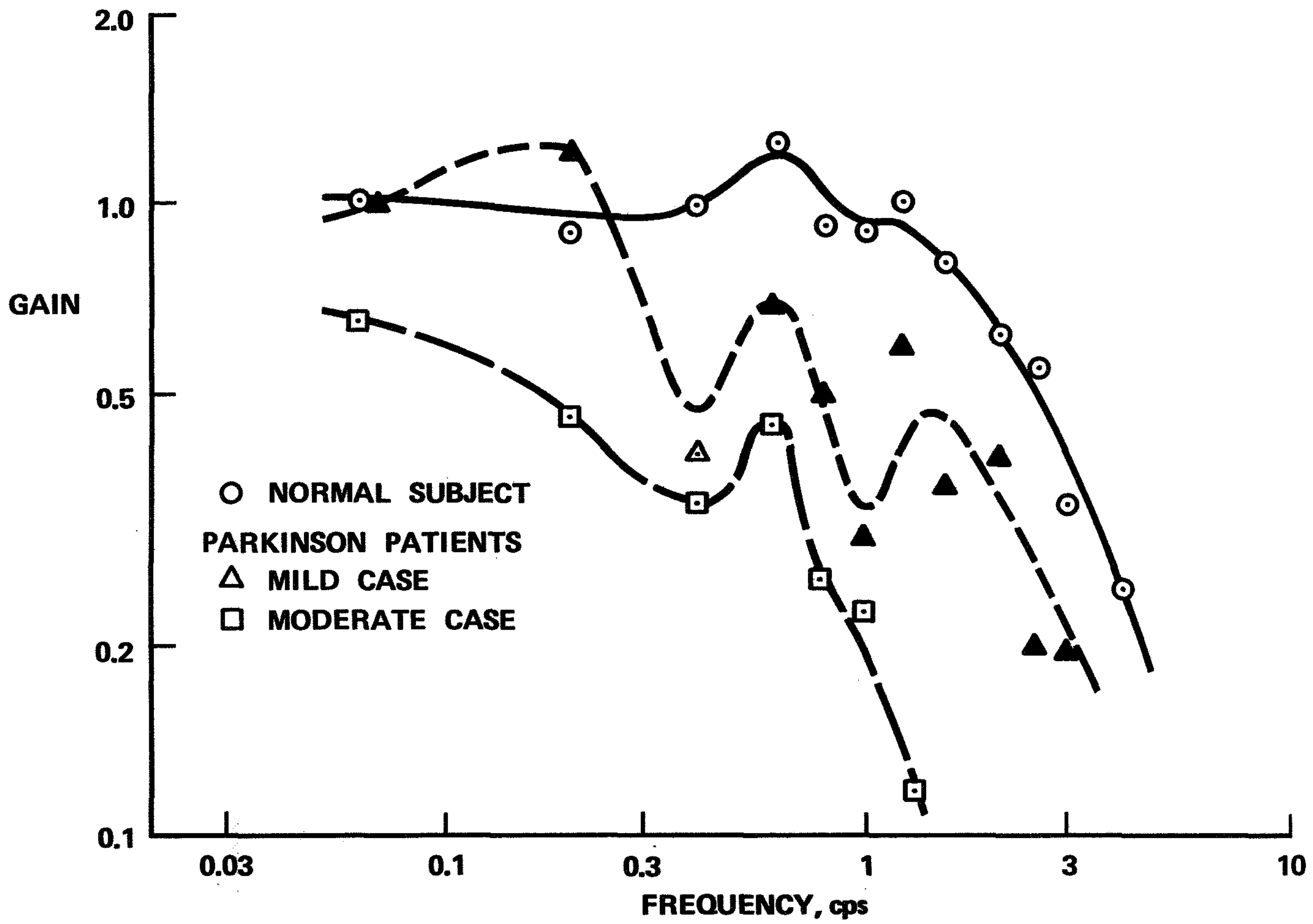


Fig. 18-3.– Effect of Parkinson's Syndrome on subjects, frequency-response gain data.

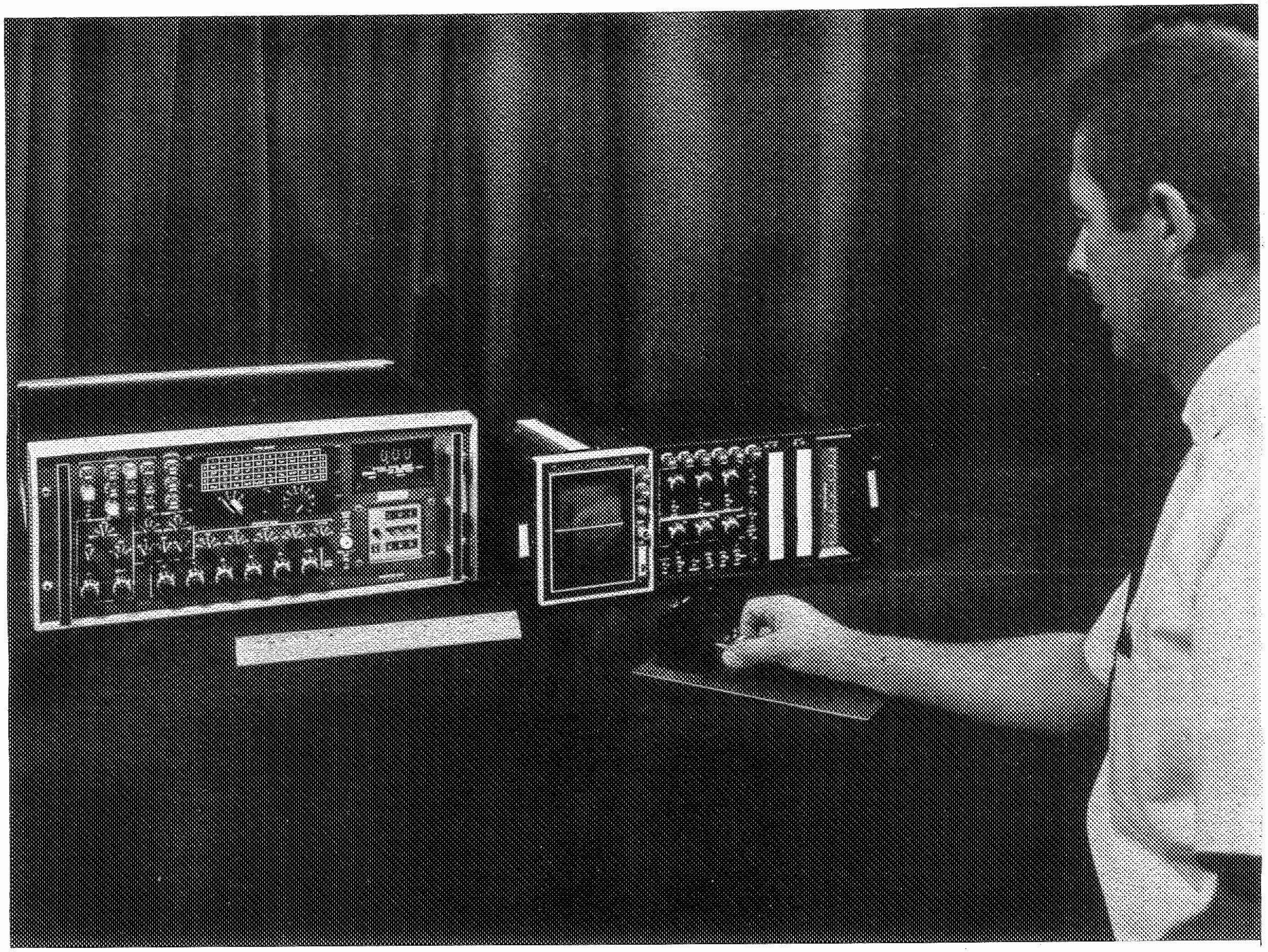
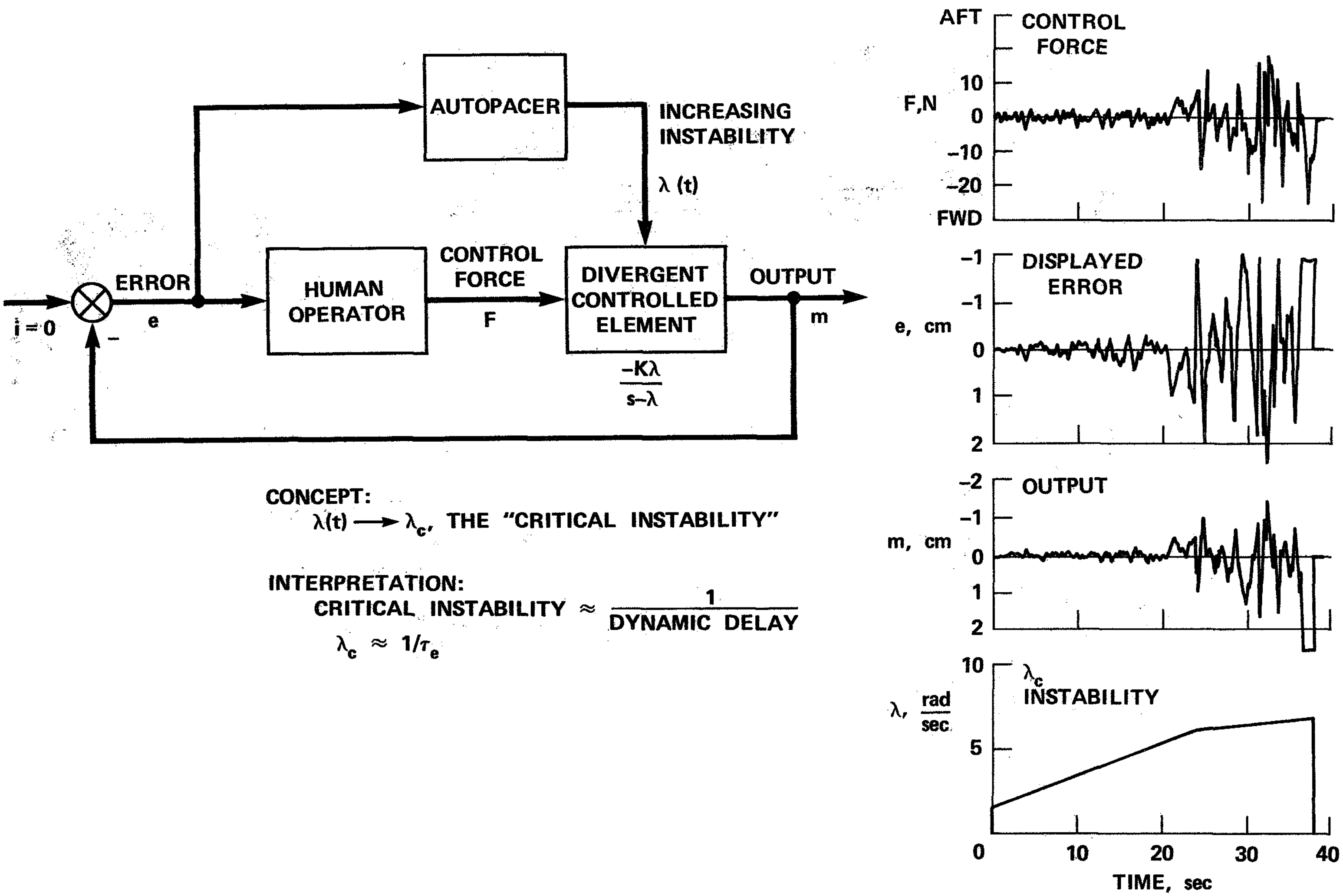


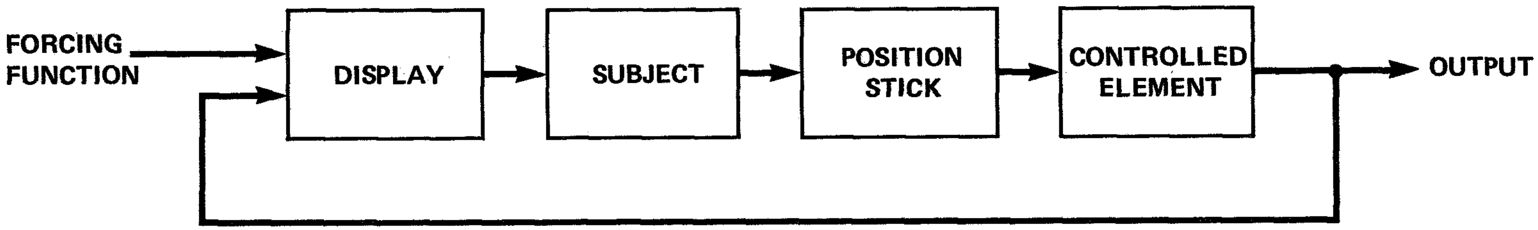
Fig. 18-4.– Critical Tasks Battery.



a) BLOCK DIAGRAM

b) TYPICAL TRIAL

Fig. 18-5.– The "critical instability" task (first order).



TYPE OF TRACKING	FORCING FUNCTION	DISPLAY	CONTROLLED ELEMENT	PERFORMANCE MEASURES
STEP	RECTANGULAR PULSE WITH ALTERNATING ±14 CENTIMETER AMPLITUDE AND PULSE WIDTH FROM 2.7 TO 5.7 SECONDS.	PURSUIT	K	REACTION TIME MOVEMENT TIME
RANDOM	RANDOM NOISE WITH CUTOFF FREQUENCY OF 1.0 rad/sec.	COMPENSATORY	K	INTEGRAL OF ABSOLUTE ERROR
CRITICAL	NONE	COMPENSATORY	$\frac{K}{S-\lambda}$; λ_o = 1.0 rad/sec $\dot{\lambda}$ = 0.05 rad/sec	RECIPROCAL OF CRITICAL ROOT

Fig. 18-6.– General tracking diagram and task descriptions.

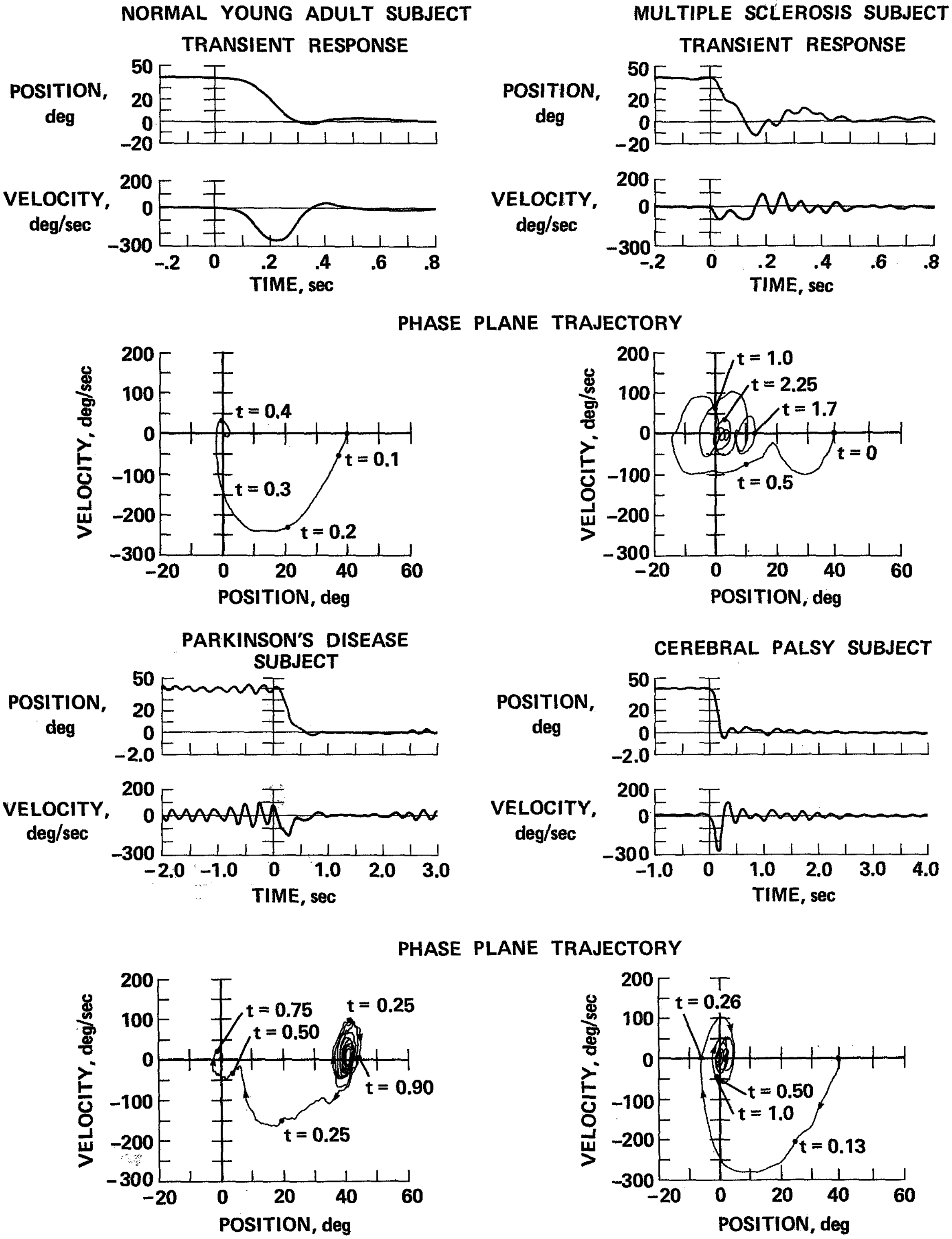


Fig. 18-7.– Time-history and phase-plane plots for normal and neurologically handicapped subjects.

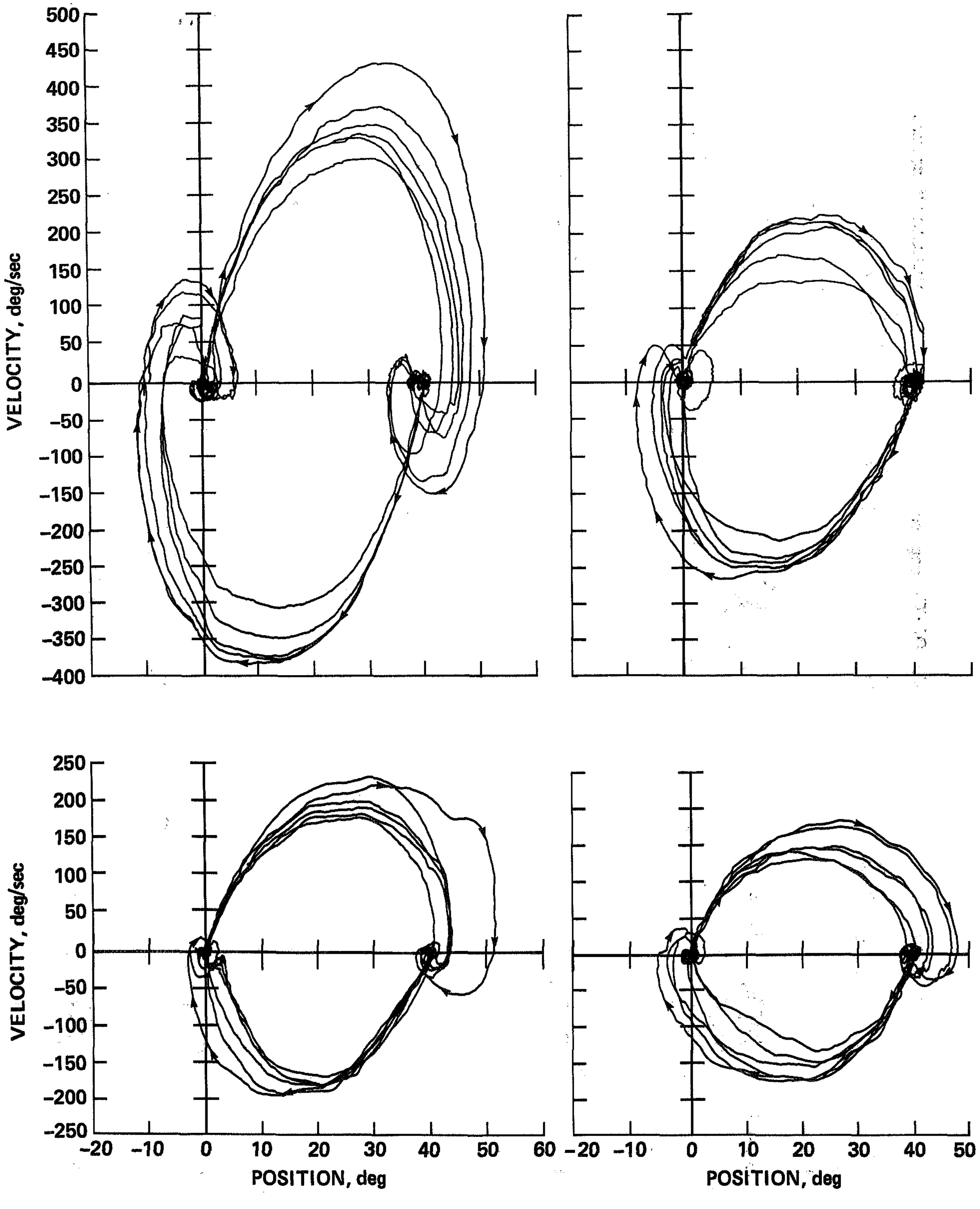


Fig. 18-8.– Phase plane trajectories of normal young adult subjects.

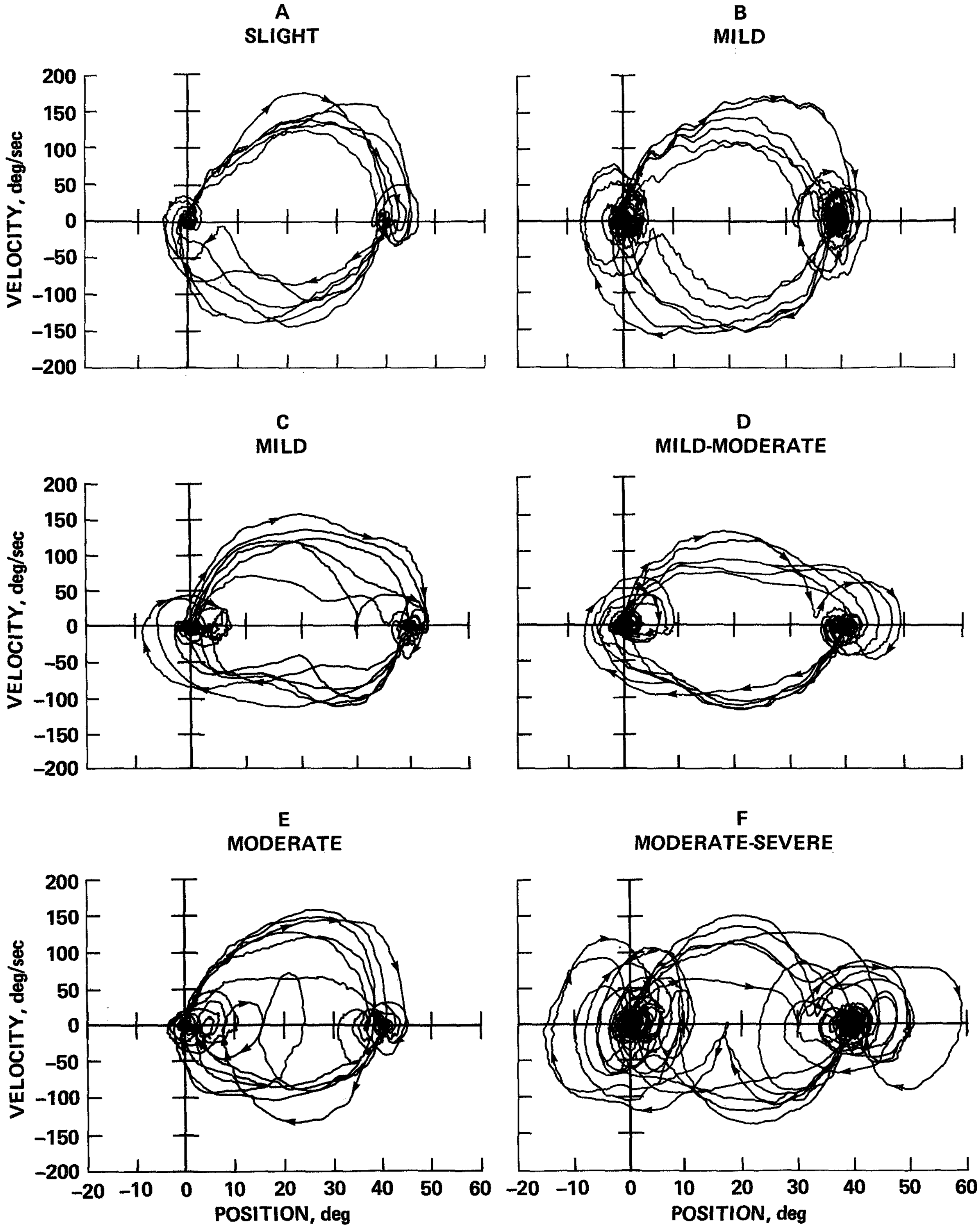


Fig. 18-9.– Phase plane trajectories of patients with multiple sclerosis.

Chapter 19

NEUROLOGICAL APPLICATIONS OF MAN–MACHINE SYSTEMS ANALYSIS

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The point has already been made that the language and techniques of control theory provide an appropriate structure for the quantification of human dynamic behavior. In fact, *man-machine analysis* here refers specifically to control theory as applied to the analysis of man's dynamic activities. Now, the scope of such an application is very broad in general, but for this discussion we restrict it to a very definite and limited set of circumstances, which we will call *small perturbation control tasks*.

CONTROL SYSTEMS

Figure 19-1, similar to Sadoff's Figure 18-1, is the block diagram showing that the human operator, acting on sensed quantities provided by a display, puts out manipulative actions which cause a controlled element to behave in some appropriate fashion. Ordinarily, this "apppropriate fashion" is to have the system output follow the system input. Everyday tasks of this nature that fall into this sort of a context range from sophisticated, like flying an airplane or driving an automobile, to very mundane, like threading a needle. Because the system here is a closed loop operation, it is relevant that the human's dynamic behavior be quantified in control engineering terms such as *time delay* (or *latency*) and *equalization.*

Equalization refers to the task-specific dynamic characteristics adopted by the human operator in his attempt to offset or compensate for the deficiencies of the other elements in the control system. One example is a very elementary control system (Fig. 19-2) where the controlled element dynamics are those of a simple integrator in which the rate of change of the system output m is proportional to the controlled-element input c. In other words, a step function into the system's controlled element will result in a constant velocity output. In this system, the controlled element dynamics are often called those of a rate command system.

In the operation of this system, the human operator is confronted, on a display, with an error – a difference between a system input and the system output. His problem is to make the error as small as possible – that is, to attempt to make the system output m follow the system output i. Now, if we subject the system to a random appearing input, such as the one shown, you will notice that the operator's control action results in a system output that follows the command input really quite well – a little shaky perhaps, but nonetheless quite well. In accomplishing this desirable feature, the operator has a small error left. You will notice a difference in scales, the error scale has been magnified to five times that of the output and the input. You will further notice that the operator's control actions (his output) looks a great deal like the error stimulus to the operator. In fact, it is almost directly proportional to it, albeit with an effective lag, a control lag that we identify as a *time delay*, or a latency. Now, if the operator's output was precisely proportional to the error with the pure time lag, the operator would then be operating with no equalization. His transfer dynamics would be a pure gain (no lead or lag equalization) and a time delay.

The second example (Fig. 19-3) is somewhat more complicated. Here the system under control is made up of two integrators, a K/s^2 system, so if the operator put a step function into his manipulator the system output would be a constant acceleration.

In this instance, the operator's task is precisely as it was before – to make the error as close to zero as possible and thus to make the output follow the input. Again, you will notice in these typical tracking runs that the forcing function is matched fairly well with the system output but that there is some error left over. Note also that now there isn't the same proportionality between the human operator's output and error as there was in the proportional control case; instead, the control actions are much more pulse-like. If you look very closely and long at this particular trace, you can lead yourself to believe that the sign of the operator's output is roughly proportional to the magnitude of the error a fraction of a second previously. If we examine it analytically, we find that the operator's output less an effective time delay is approximately proportional to the rate of change of the operator's input. In other words, the operator is developing what we will call a *low frequency lead* as his equalization.

These two examples introduce two points about the control functions with which we wish to quantify operator behavior. The first of these relates to input-output relationships; for these, we talk about latencies, time delays, gains or proportionality factors between operators' inputs and operator outputs, and equalization – that is, the operator's output is roughly proportional to some function of the stimulus. The second characteristic introduced is that the operator's output is never precisely related to the stimulus in terms of simple things. Instead, there is an additional uncertainty or what we can call, for the moment, *operator-induced noise*.

Both these kinds of properties can be measured and quantified in great detail using cross-spectral analysis techniques and other control theory methods. For example, they can be modeled quite effectively, as Mann notes in Chapter 13, with the use of analog or digital computer simulations. In the most common form, however, for manual control theory, the human being is characterized as a quasilinear device, and his operations are broken into two components. The first is the result of a set of transfer characteristics operating on the input. These transfer characteristics are functions of all the variables imposing themselves on the human, such as the task variables (e.g., the controlled element dynamics and display characteristics), the environmental variables (e.g., ambient temperature), and so forth. The other component is the result of a noise-like random signal, operating through the operator's transfer characteristics. This additional output, called the *remnant*, is the part left over from linear operations and is needed to make the actual system output equal that of the model. The remnant is the operator-induced noise. When carefully measured, and expressed in terms of a power spectral density, it appears as a broadband continuous function.

Sadoff (Chap. 18) mentioned that these kinds of measurements have been made for over 25 years, for more and more complicated situations. In general, the block diagram in Figure 19-1 represents both a multiloop system and a multimodality situation. Attending the growing catalog of data has been the development of predictive models. These models have as their prime intent the estimation of behavior for novel situations not covered by extant data. These topics are now very well advanced. They are treated in graduate courses in several universities and they are commonly if not universally used in the engineering design and assessment of complex man-machine systems. The use of these models in the design of individual transportation systems for the handicapped is an obvious example of what Wyatt (Chap. 2) called *imitative transfer*, although the process of making appropriate modifications to these models to accurately characterize the degradation in dynamic response characteristics of the neurologically handicapped is probably more in the nature of what he has referred to as an *adaptive transfer*.

OBJECTIVE MEASUREMENTS

In recent years, the precision and dynamic range of measurements taken with the total human being has increased so much as to enable us to perform a crude kind of what I will call *dynamical dissection of* *the human* in the sense that certain of the measurements made can be associated with certain portions of the human. Even the simplest example of this concept is still relatively complicated. We first set up the controlled element dynamics in such a way that the equalization demanded of the operator approximates a pure gain. We can do this by adjusting the controlled element dynamics $Y_c(j\omega)$ to approximate the form $K_c/(s-a_1)$, which is a simple first-order diverging controlled element. The dynamics of this device, if simply left to itself with some initial conditions starting it, would result in a divergent response with the rate of divergence being a function of the root a_1.

This form of transfer characteristic with a_1 taken at a value of about 2 radians/sec has several specific advantages; that is, it induces roughly proportional control by the operator, emphasizes the high frequency characteristics of behavior, and minimizes the operator variability. For this controlled element form we have a large amount of describing function and remnant data over a broad frequency range for the human as a total entity. Now we are going to try to take the man apart. To do this we take a set of component characteristics and then remove these characteristics from those of the total human. For the first of these, we work on removing the neuromuscular subsystem dynamics. Now, this subsystem, as shown in Figure 19-4, comprises motor units, sensory organs, and associated neurological apparatus, which provides the output actuation system for the human.

To make these matters as simple as possible, we will have a force stick as the manipulator used in this situation so that the joint receptors are probably uninvolved and the primary receptors are ensembles of spindles and Golgi end organs.

Figure 19-5 depicts this general situation with some more emphasis on the electromyographic properties. We have used surface electrodes to pick up signals from agonist and antagonist muscle bundles. With rectification, filtering, and proper mixing, you can get a signal out that is roughly proportional to the firing frequencies, and then these in turn can be calibrated and interpreted in terms of the average tension during the run and the differential tension at any time. The differential tension, of course, activates the human's output (Fig. 19-6).

The average tension is an important set-point variable in the control dynamics – it determines the steady-state operating point about which the small perturbation dynamics work. We can set this average tension at a specific level by means of one of three different techniques: (1) change the forcing function bandwidth, (2) change the size of the unstable controlled element divergence root, or (3) show a display for the operator to maintain a given steady state tension level. These are effective means of modifying the amount of gamma discharge and consequently the steady-state tension level.

By processing signals such as these, we can find the describing function G_m, which is that between the neuromuscular subsystem output motion and the pseudo motor input x (Fig. 19-5). We get results such as those shown on the frequency response plot of Figure 19-7. Note the dynamic range of the measurements. In amplitude, they cover a range of about 40 dB. In frequency, they vary from about 0.3 to 70 radians/sec. Now, this is very, very large indeed in both of those dimensions.

Note also that there are cross-spectral measurements (diamond symbols) – what I call ratios, of "closed loop" cross-spectrum measurements such as C/X – interlaced with "open loop" cross-spectral measurements. The latter are taken by cross-spectral analysis between the signal x and the signal c. Since these do interleave so well, they indicate first that either way of measurement is satisfactory, and second that the principal source of the remnant in the human operator is elsewhere than in the neuromuscular system – in fact that it is in front of the neuromuscular system.

We can now fit these data with various and sundry curves (Fig. 19-7). The one shown here is for a third-order transfer function plus a small latency – a first-order root at 40 radians/sec and a second-order, 0.8 damping ratio quadratic pair with an undamped natural frequency at 11 radians/sec. The adequacy of the curve fit is shown by comparing the solid lines with the data points. The dynamics of the fitted describing function can be then considered parameters or one can take his favorite muscle model, whatever it happens to be today, and solve for the muscle model parameters that are consistent with these fitted dynamics or the data themselves.

In any event, we now have the describing function for the muscle units, and we already have the describing function for the total system. Figure 19-8 shows the total human dynamics form, from the display input to the manipulator output. In terms of this figure, we also now have data for the "muscle actuation" characteristics and the total characteristics from *e* to *c*. If we look at the spindle ensemble characteristics as those of a simple lead-lag, we can then manipulate the muscle actuation and total human data so as to "open" the neuromuscular loop and obtain estimates for the lag characteristics of the spindle ensemble.

So far, we have dynamics for the muscle actuation units and the neuromuscular sensor units. We also have, as leftovers for the front end – that is, the more central activities from alpha motor command back to the display input – an effective latency and a pure gain. Thus all three "boxes" in the total human are separately identified and quantitatively known. If we do this experiment again, changing the controlled element dynamics so as to induce a different set of low frequency equalization characteristics, then taking out the neuromuscular system, and finding the sensory feedback characteristics and the muscle actuation characteristics, we quantify these boxes for a number of systems. Comparing these data we find that the neuromuscular properties remain essentially constant so long as we adjust the average tension to the same level. We also find, on the other hand, that the more central properties change. The predominant variation, of course, is the low frequency equalization, which is needed to stabilize the control system. Associated with this is a change in the residual latency.

In Figure 19-9, the residual latency is shown as a function of the low frequency lead equalization. Zero lead units is a pure gain (proportional control). Plus one lead units is very low frequency, first-order lead; plus two units is very low frequency, second-order lead, etc. The time delays are plotted as inverse functions because in this form they are normally distributed, and it also happens that the variability of the inverse time delay is a constant. The effective latency for the total human – and this particular plot includes the effective dynamics of the neuromuscular system as an additive component to the central latencies – ranged from about 0.3 sec for the pure integral control case (−1 lead units) through 0.8 sec for the second-order leads. The increments in these latencies are the cost of generating the increased low frequency lead equalization. They also have to be associated with differences in the neural pathways and the neurological apparatus associated with the generation of each distinctive form of control behavior.

This last point, I think, takes us back a century or more ago to the very earliest work in the reaction time studies of Helmholtz, Wundt, and others. They looked at a large number of situations that exhibited different reaction times and tried to attribute these differences to various things. In their day, their attributions often turned out to be wrong, and I hope that the present argument doesn't follow the same path.

We have discussed the kind of crude dissection of the total human into the detailed dynamics of the neuromuscular system, the motor units, some peripheral sensory units, and the detailed dynamics of the central equalization functions and the latencies. We can generalize all these results much further to take account of, for example, the joint receptors, by not using force or pressure manipulators but instead using free moving manipulators. We can also generalize them, as Young discusses in Chapter 17, by taking into account the dynamics of the motion sensing apparatus and so on. These descriptions are in themselves very complete quantitative descriptions of human control properties. They are what I would call extremely objective measures. Everything that has been done with them in detail so far has been for normal subjects – most of them test pilot subjects. Unquestionably they will be different in detail and perhaps in quite specific details for subjects who are afflicted with neurological degradation at various and sundry locations within the nervous system. So far, we have neglected the remnant, which is sensitive to changes in environmental variations such as vibration or acceleration and to changes in operator-centered variables such as fatigue. Because the remnant is so sensitive to operator-centered variables, it would be very surprising if it were not a sensitive measure of the degree of neurological disorders as well.

To better appreciate and quantify the human dynamic correlates of various neurological syndromes, the sort of detailed dynamic measurements discussed here could be conducted on neurologically disordered patients and then carefully and fully correlated with the clinical manifestations to create a medical history plus a control dynamic history. These should significantly help to improve our in-depth understanding of the phenomena involved.

The types of measurements described are simple and definitive, and easy enough to accomplish on a research basis on a limited number of subjects. For a very large number of subjects, however, they are probably far too complicated. There is another, much simpler, category of measurements, which Sadoff has mentioned and Repa has already applied in at least one form (Chap. 18). These are the so-called "critical task measures," which are set up to quantify the behavior of the human for the several limiting conditions of interest. These include conditions where he is operating pretty much as a proportional controller, conditions where his output is a function pretty much of the rate of change of his input, and conditions where his output is a function of the rate of change of the rate of change of his input. Figure 19-10 shows a very high correlation showing the relevance between the effective latencies and these critical task scores.

DISCUSSIONS

Q. Since the concern at this conference would be in applying these descriptions to neurological problems in a normal environment, (in which there has been relatively little research except what Repa reported on), perhaps you might comment about the sensitivity of these models in normal subjects in an unusual environment. In what way do the parameters change with stresses?

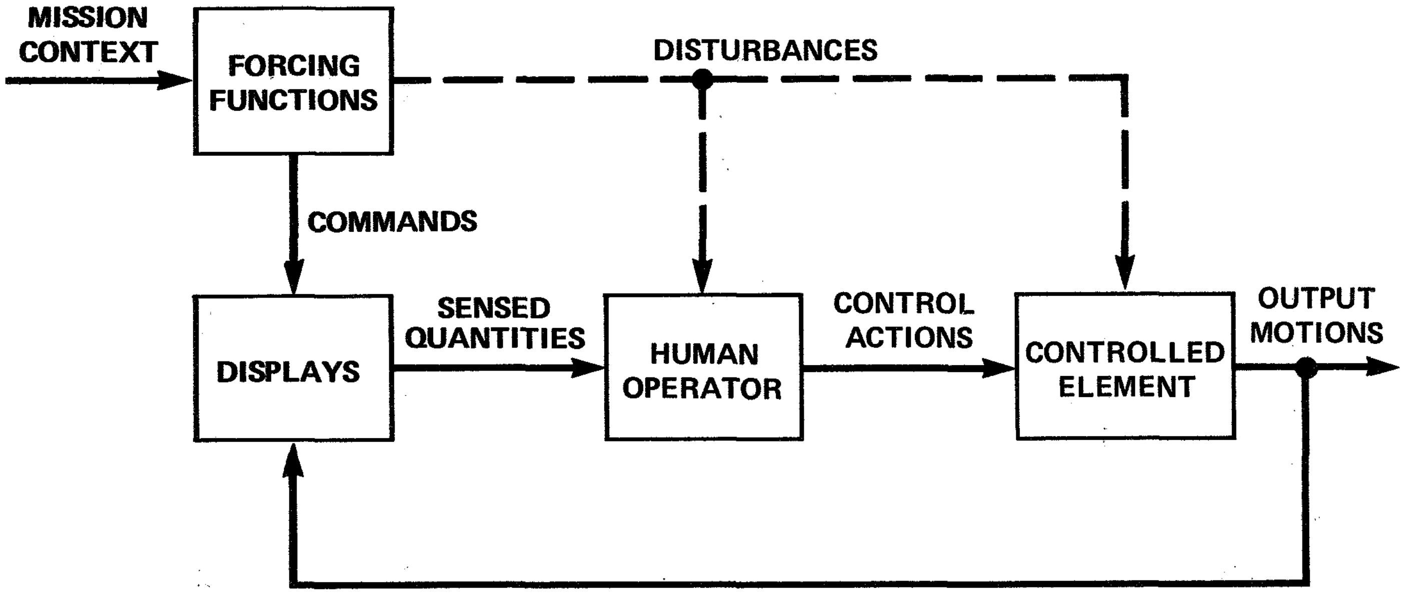
A. Well, for example, you have heard Brian Repa's comment on the way the effects on the critical task scores change under certain drugs. Critical task scores have been shown in our laboratory to be pretty sensitive to other drugs, such as alcohol. We also have conducted experiments here at Ames, again using critical task measures, on the effects of vibration and acceleration. Here again, the scores are sensitive to these stressors.

Sadoff: We also got significant changes in the first-order critical task scores during the imposition of mild Coriolis force stimulation in some of our experiments on the human centrifuge.

Q. I just wanted to add to the question the variable of age, since that seems to be a rather different order of variable from, say, drug effects. I was wondering if you have any information.

A. We haven't run enough subjects to have a repetitive sample with age. With all these measures, the best results are almost invariably obtained utilizing the subject as his own control. And we haven't had subjects that long.

- TASKS CONSIDERED REQUIRE THE OPERATOR TO ACT AS A PRECISE, ADAPTIVE, SENSORY-MOTOR LINK IN A CLOSED-LOOP SYSTEM



- SYSTEM OPERATION IS CLOSED-LOOP, SO HUMAN DYNAMIC <u>BEHAVIOR IS QUANTIFIED</u> IN CONTROL TERMS, SUCH AS TIME DELAY (LATENCIES) EQUALIZATION, AND OPERATOR-INJECTED NOISE (REMNANT)

Fig. 19-1.– Man-machine analysis.

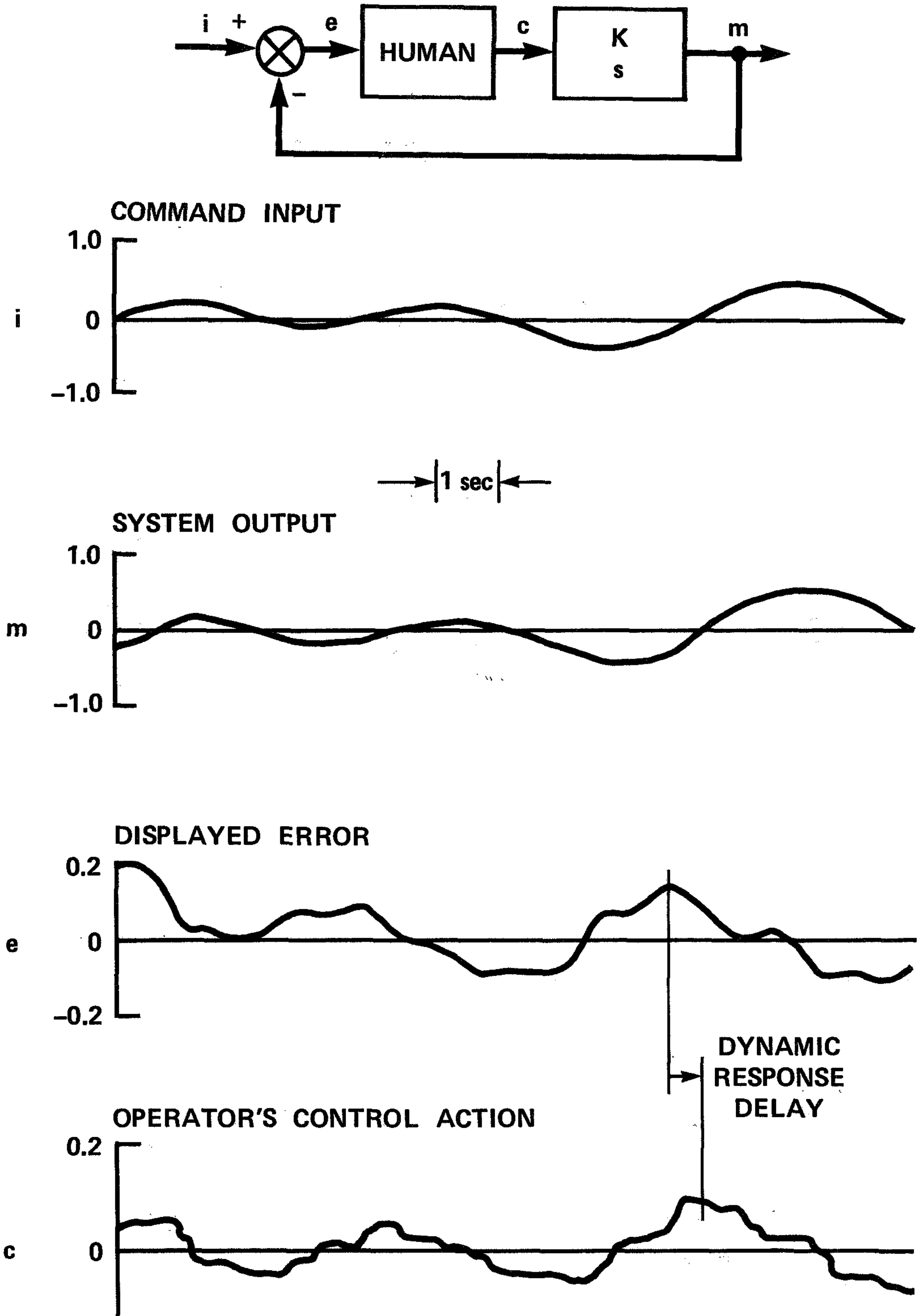


Fig. 19-2.– Time history of proportional control.

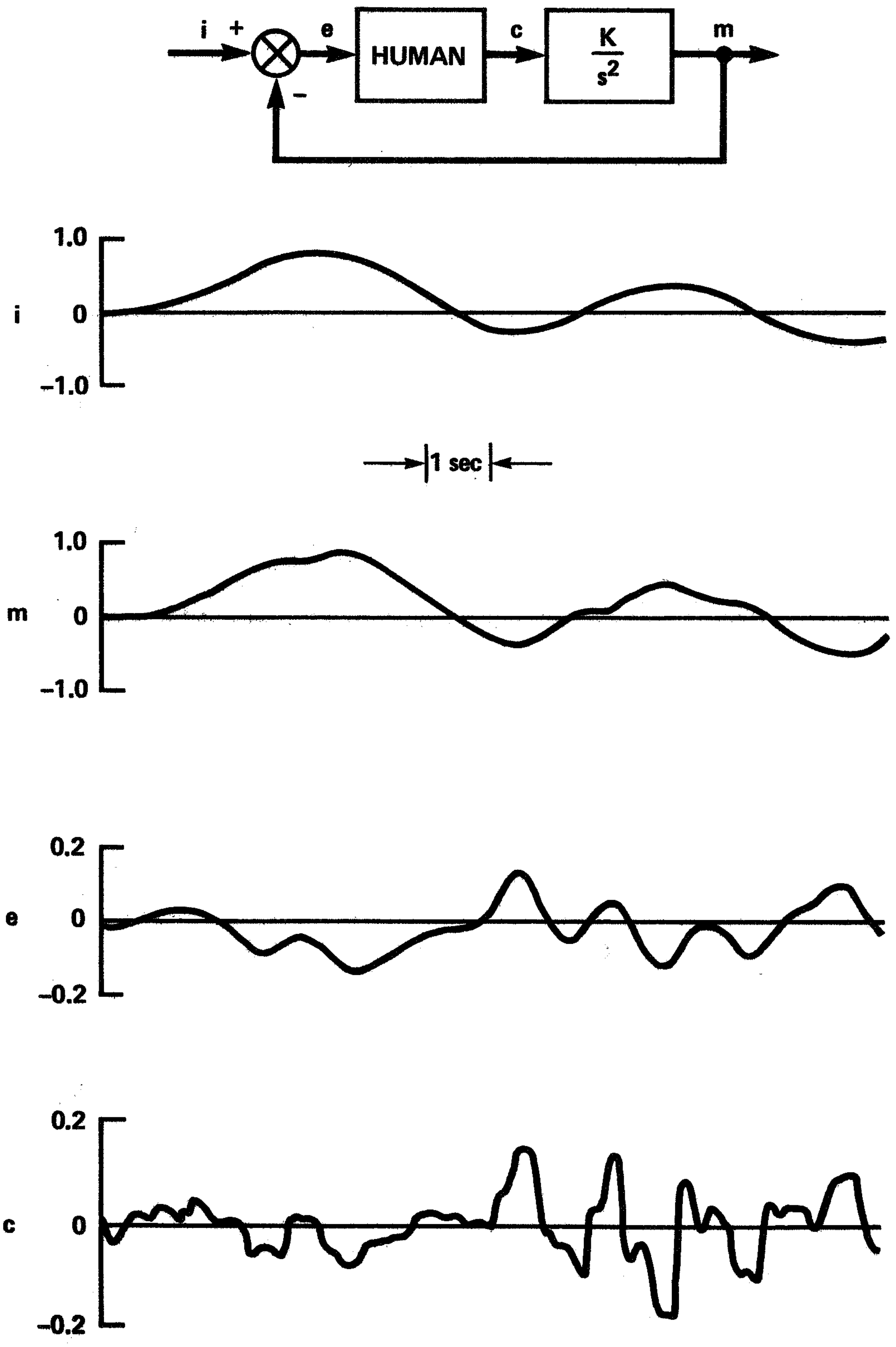


Fig. 19-3.– Time history for lead generation.

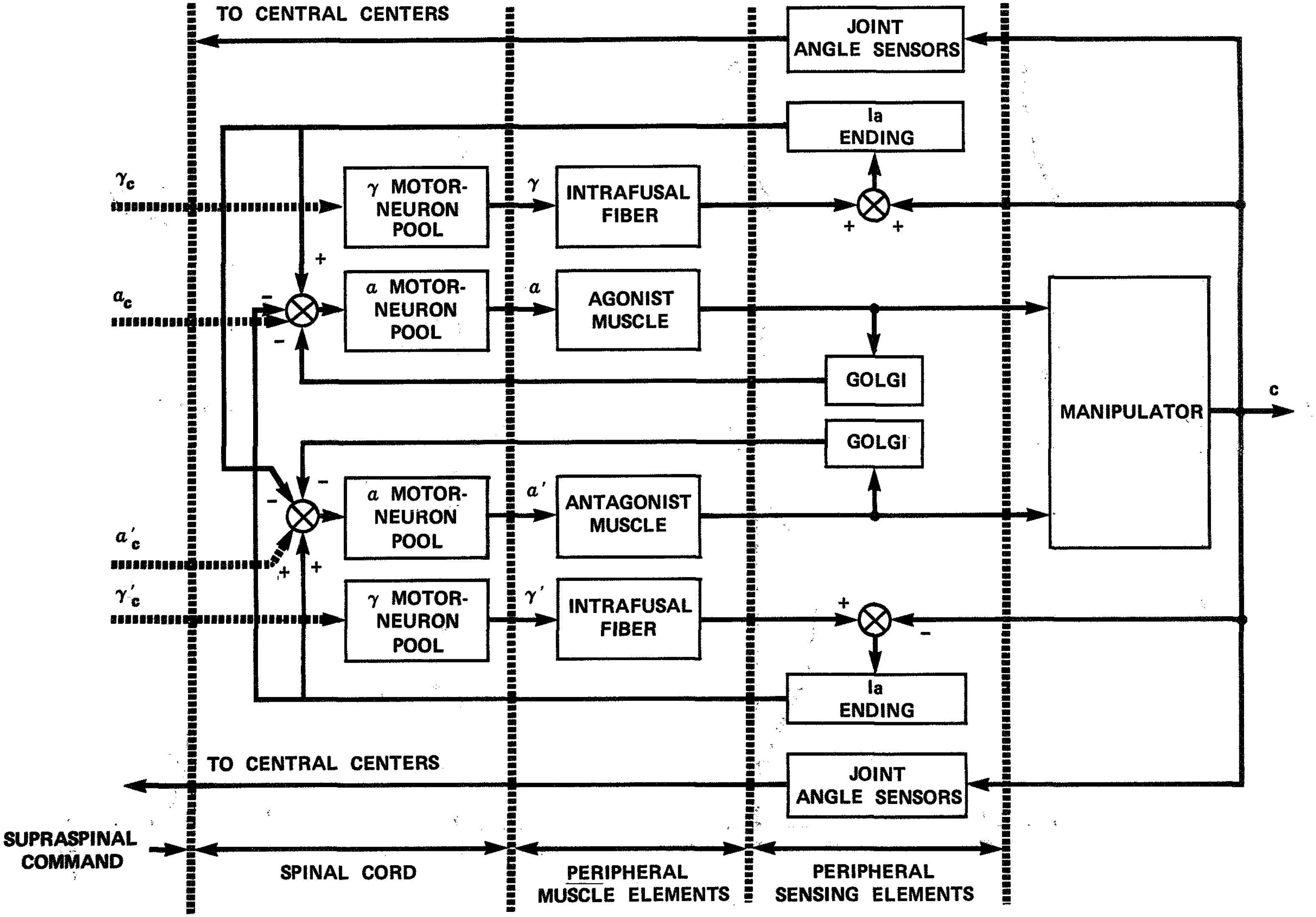


Fig. 19-4.– Functional diagram of agonist/agonist neuromuscular system elements involved in tracking.

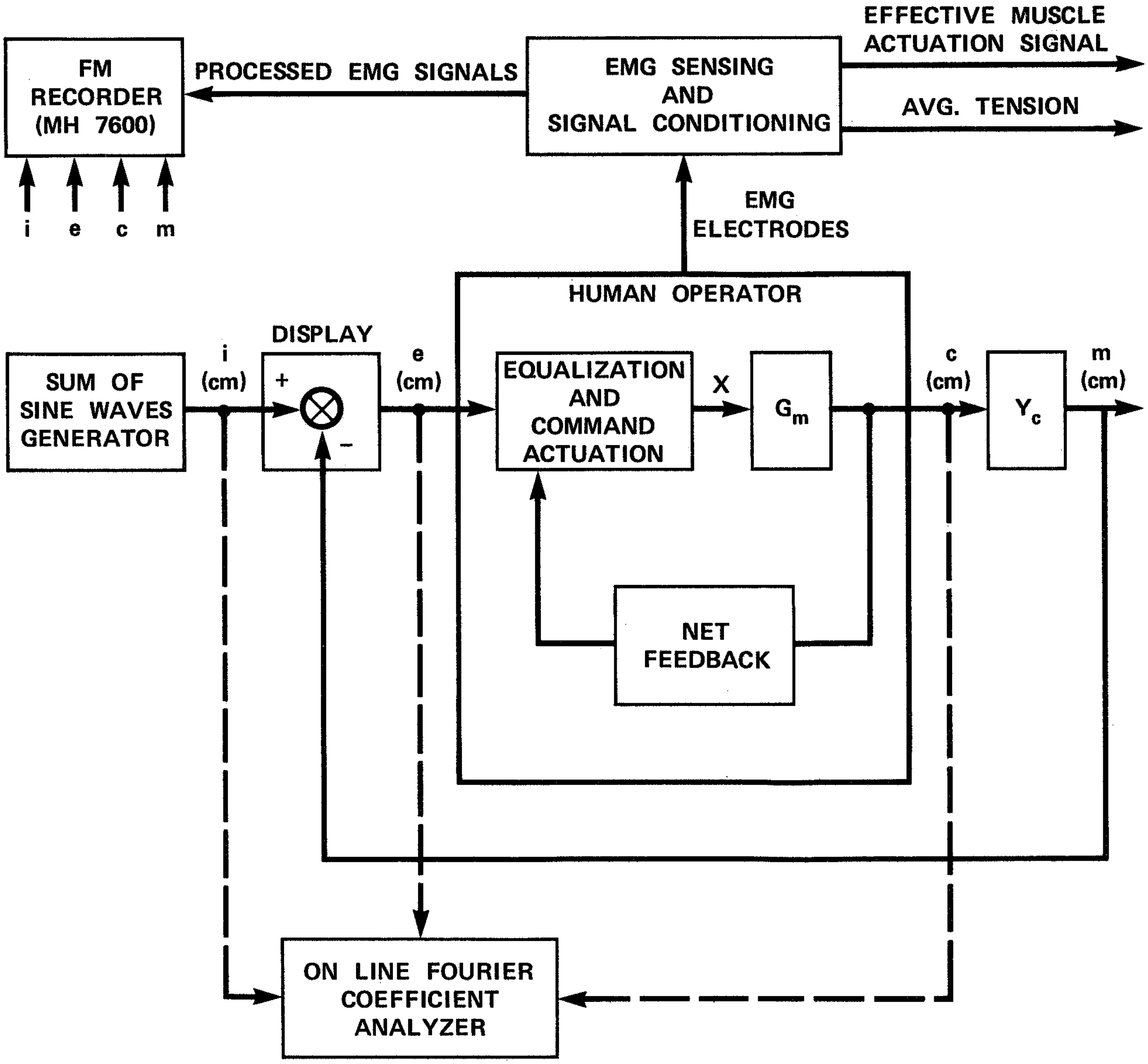


Fig. 19-5.– General arrangement of equipment.

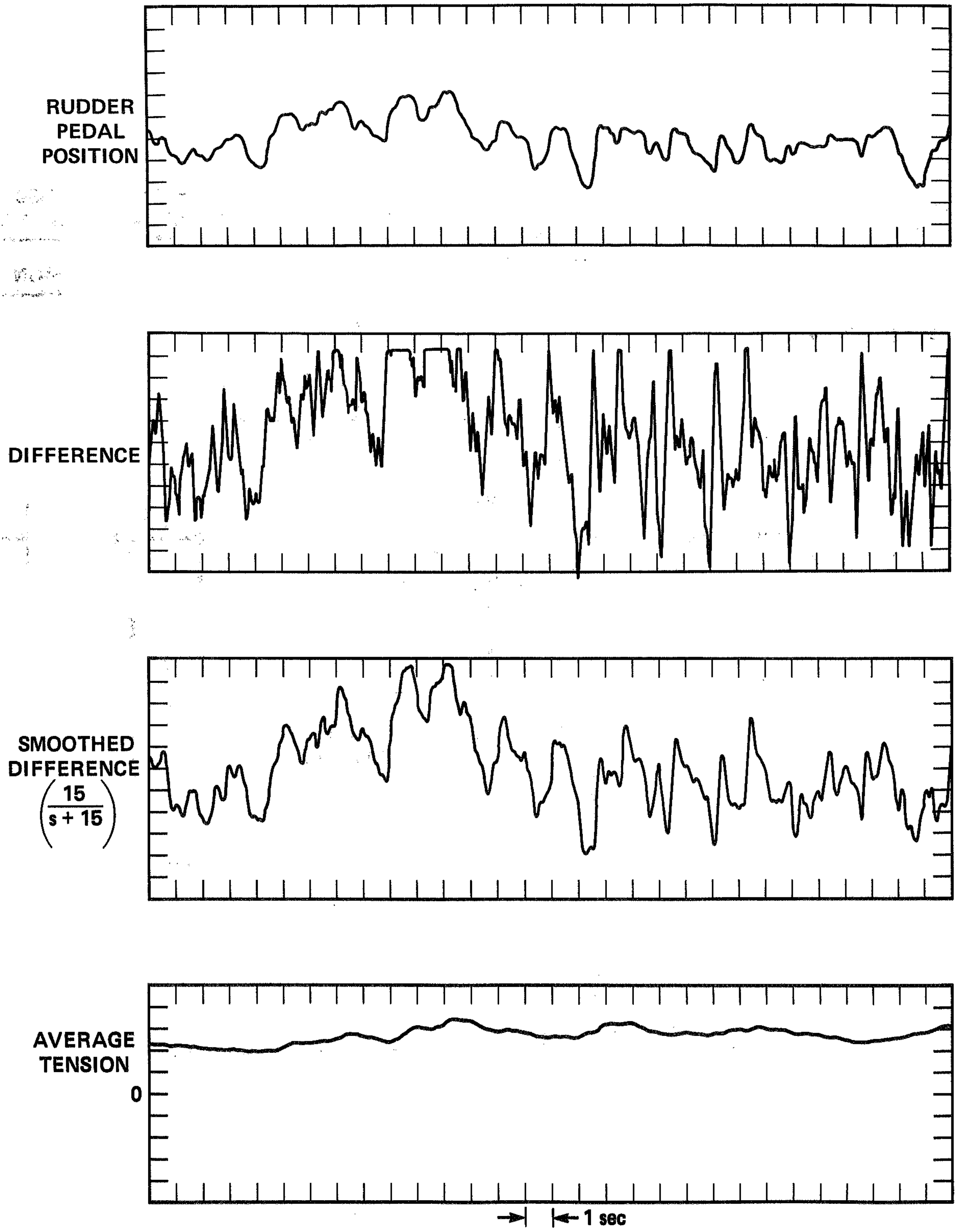


Fig. 19-6.– Example time history for EMG signal processing; $Y_c = K_c/(s-2)$.

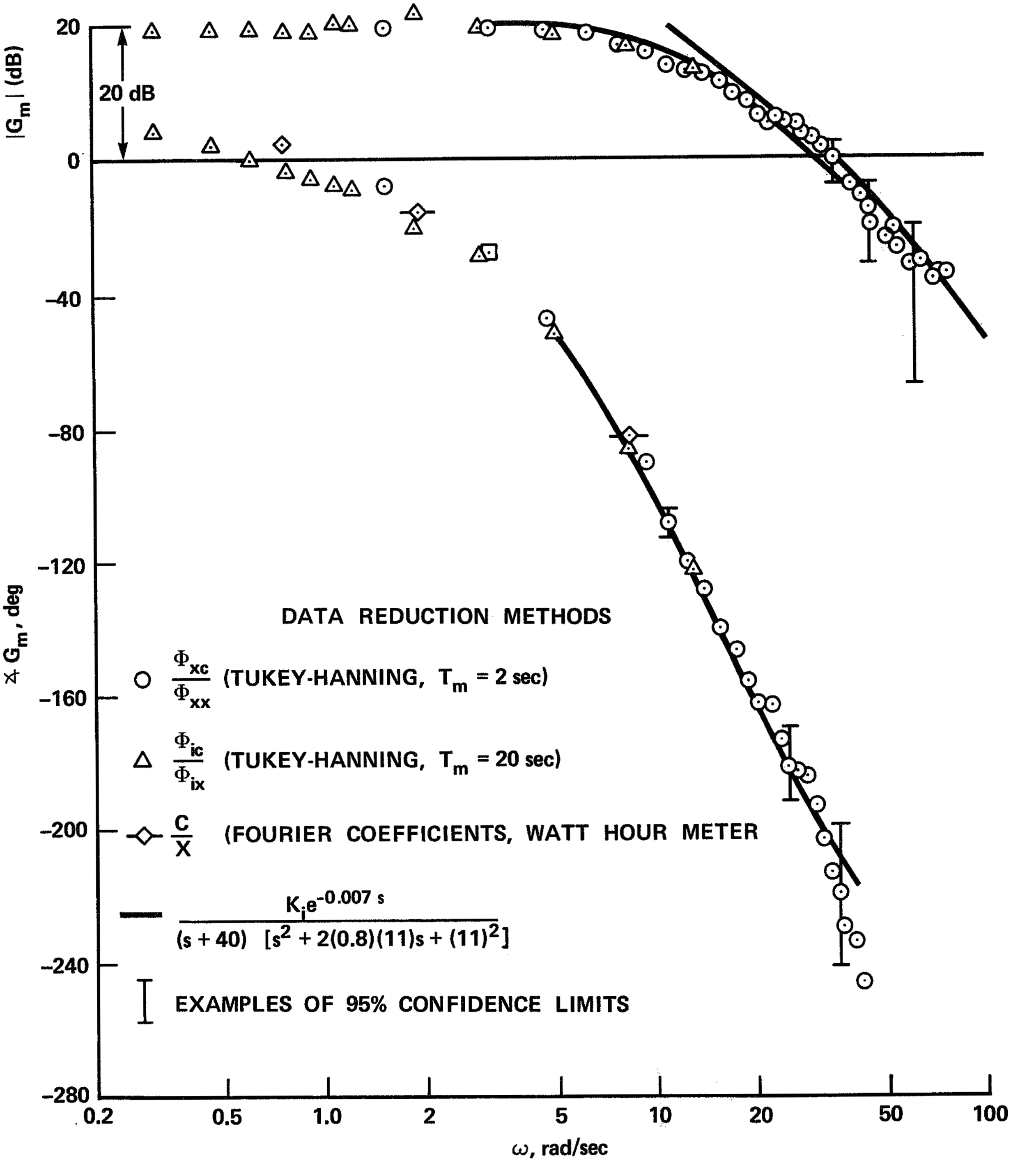


Fig. 19-7.– Muscle/Manipulator describing function, G_m, rudder pedals, $Y_{c_1} = 1/(s-1)$.

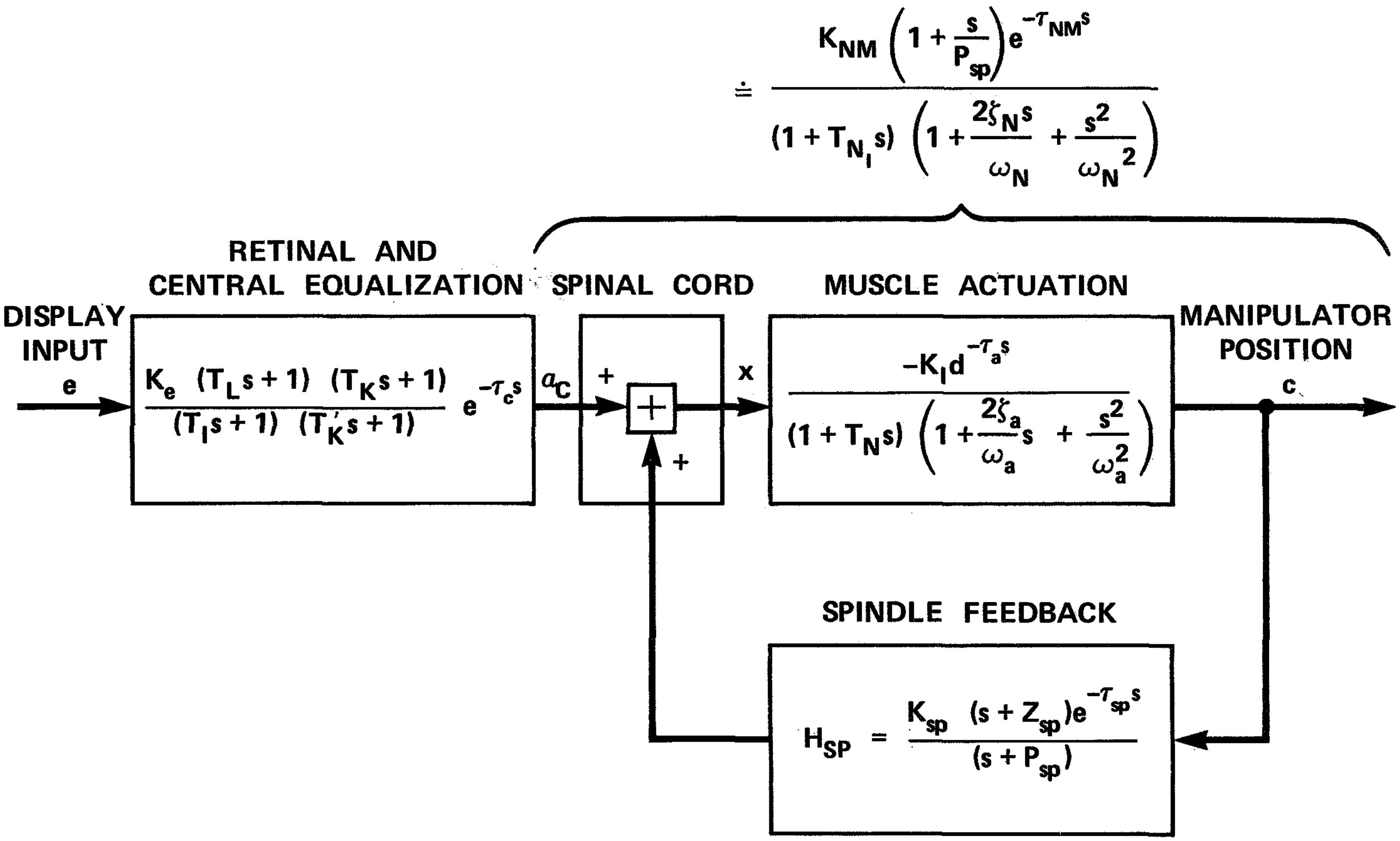


Fig. 19-8.– Neuromuscular subsystem for pressure manipulator and central equalization form for first- and second-order dynamics.

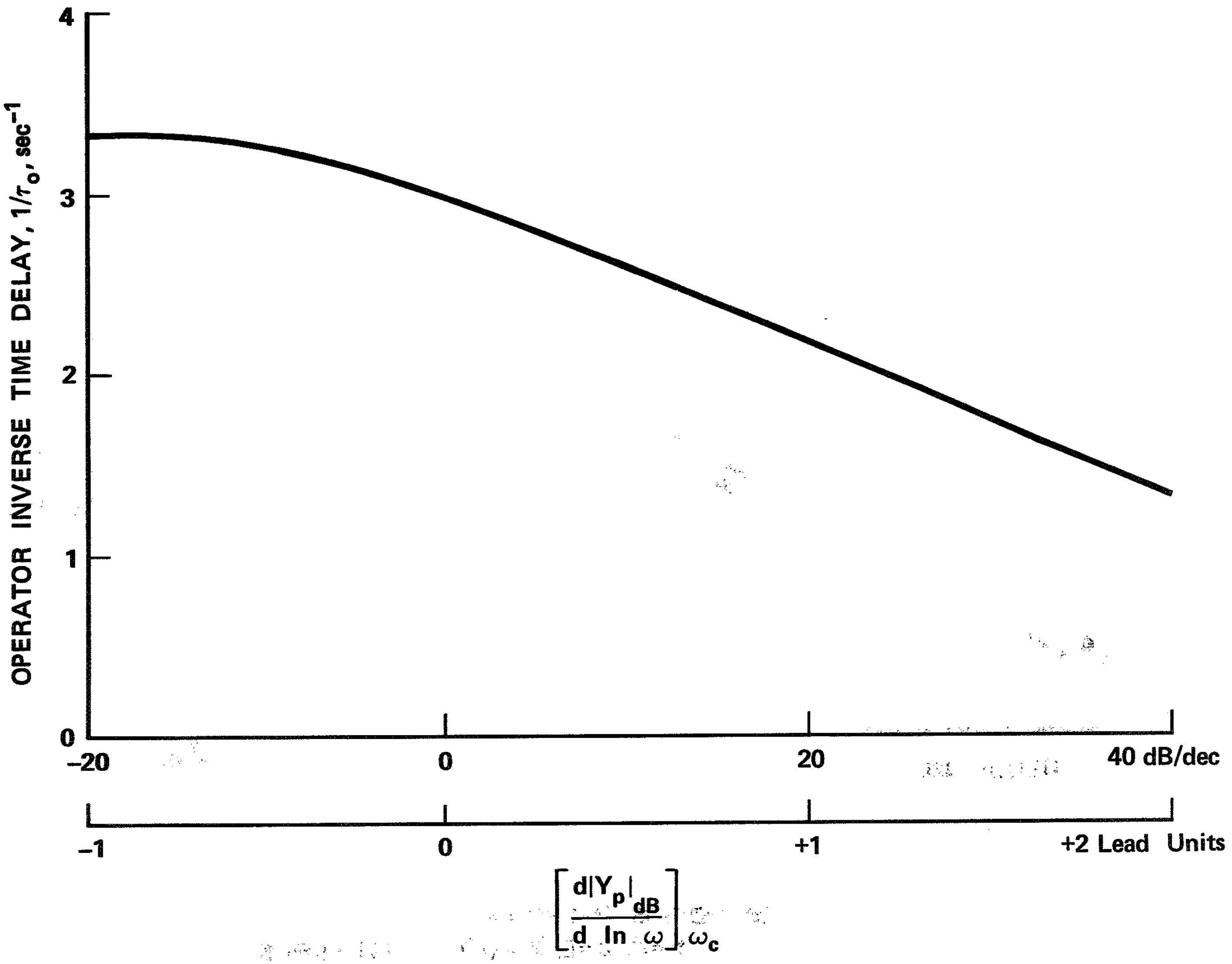


Fig. 19-9.– Variation of dynamic stimulus-response latency with degree of operator lead.

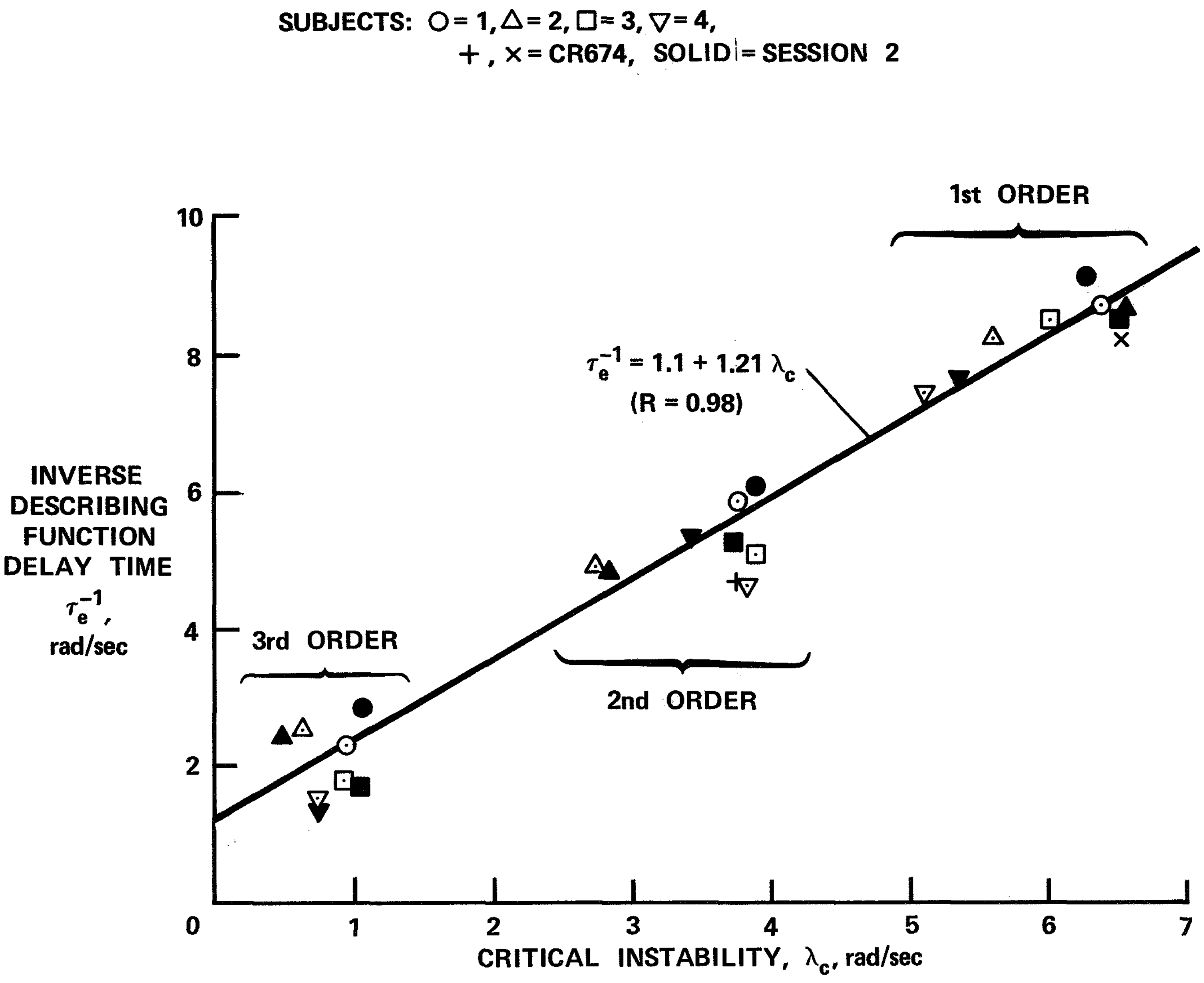


Fig. 19-10.– Connection of dynamic stimulus-response latencies with critical instability scores.

Chapter 20

NEW ENGINEERING SYSTEMS FOR MOBILITY

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MOBILITY SYSTEMS CONCEPTS AND DESIGN

Grumman Health Systems, a new division of the Grumman Corporation, has been working with United Cerebral Palsy in New York for the last two years to develop a transportation system for the handicapped. The systems approach developed to meet this objective is based on the premise that vehicles and other mobility systems for the handicapped must be designed with the handicapped's needs in mind first, rather than requiring the handicapped to adapt their disabilities, if you will, to existing systems.

Aerospace Technology Transfer and the Systems Integration Approach

It may sound unusual to many of you that a corporation that can build vehicles to land men on the Moon should become involved with problems of the handicapped. During the last few months, however, we have become very much involved in programs of this type and are finding many areas in which aerospace research can make relevant and significant contributions. One recently completed study, for example, called Mobility and Restraint Devices for Space and Space Stations, has been very helpful in providing solutions to the problem of safety restraint systems for the handicapped. Figure 20-1 shows a flexible waist tether and belt developed for the mobility and restraint system of a spacecraft. The device will be made of a nonflammable material, which is quite rugged. It could be used for the neurologically disabled. A slide mechanism on the belt allows good mobility and yet restrains the handicapped person while he is in the vehicle.

Figure 20-2 shows another concept for the mobility system—the use of inflatables as a means of providing comfort and security for the handicapped. This particular inflatable mid-torso restraint system which contains a bladder valve, allows the individual to sit very comfortably and yet securely. These devices will not necessarily be implemented exactly as shown, but they are among the many concepts developed and being considered for our mobility system.

Grumman's forte will likely continue for sometime to be in the area of systems engineering and systems integration. In the Lunar Module Program, for example, although we fabricated that vehicle, only some 40 percent of it was actually built by Grumman. The rest was "systems integration" by the Grumman Corporation. We are utilizing the same basic approach, applying systems engineering and integration skills, in the design of a transportation vehicle for the handicapped. A recent application of this concept was in the development of a mobility systems study for the Brooklyn Rehabilitation Campus of United Cerebral Palsy. As part of this study, we developed a wheelchair train concept that will allow classes of handicapped students to move from one end of the campus or one end of the building to the other in groups in a train-like system (Fig. 20-3)—another example of the concept of integration.

Design Objectives

We defined our objectives first and proceeded to a design based on these objectives, rather than formulate a design and see if it would fit the problems of the handicapped. The major objective was to provide a safe, comfortable, and cost-effective transportation system that could transport the handicapped in dignity. Anyone who has an opportunity to travel on many of the transportation systems that provide transportation for the cerebral palsy patient will find them to be grossly inadequate on all counts.

CP youngsters around New York City must travel from an hour to an hour and a half each way between home and school. It was determined that educational enrichment on board would provide some means or methods to develop interest for the youngster, and when he reached school, he would be stimulated and more interested in being educated and learning. Education in motion is a new concept, but we consider this an area deserving great interest and investigation.

A third area is that of rehabilitation. Just as the youngster traveling to school might spend the time enroute in educational tasks, so might a handicapped person exercise and perform therapy. This concept will be evaluated in both mobile and docked modes of operation. Similarly, consideration is being given to means of recreation and vehicle conversion to a summer camper. We have developed a multimode, cost-effective vehicle for full 365-day utilization.

The vehicle concept described for the transportation of patients with cerebral palsy in the private sector from their home to the school has to be carried one step further. Many people in United Cerebral Palsy believe that if a handicapped person is not given the opportunity to get into and utilize the services of the public sector, his life is not complete (see also Chap. 5). Another important objective, therefore, is to transport the handicapped right into the cities, to enable them to get on easily and off easily and move about through stores, shopping centers, and other places where every physically normal person can go.

A basic design objective inherent in all the areas mentioned is to develop a vehicle that can be operated and maintained by even the lowest level qualified personnel. It has got to be simple.

Design Guidelines and Performance Objectives

We first felt that we had to use the systems analysis approach to meet our design objectives. That is, we had to define the man-machine requirements and problems that had to be resolved first. Note that we are defining requirements—not looking at hardware. We had to identify the vehicle operations and to define the design guidelines and specify performance objectives. Mann's discussion of mission orientation and performance measurement (Chap. 13) is particularly relevant here and describes our task at this stage quite clearly.

Basic Vehicle Design

The vehicle that we have developed ensures safety, comfort, easy ingress and egress, and security. Figures 20-4 and 20-5 show the basic vehicle. The ramp, which slides underneath the floor, is utilized specifically on one-way streets and can be most useful for suburban and rural areas. On a 6-inch sidewalk, the ramp provides a 7 degree angle of inclination, which is very low. If we decided to include an elevator, it would most likely be placed to the rear of the vehicle as well. All seats, from a safety point of view, are facing forward. We do provide for both the wheelchair and the ambulatory individual. We provide storage for books, braces, crutches, and whatever other personal articles are carried. To insure safety, we have an exit panel, which is part of the wall but becomes a ramp in an emergency.

One vehicle characteristic, which has generated exceptional interest, is the provision of bus-to-home communications. We have found that many of these clients, especially during bad weather, may sit at home, fully clothed, for periods of 15 or 20 min or longer getting terribly overheated, waiting for the bus to arrive. A bus-to-home message ensures that the client or the handicapped person is not overdressed and is waiting comfortably for the bus to appear. Thus, he need not become overheated and susceptible to colds or other respiratory infections.

Periphery Devices, Aids, and Educational Materials

Once we have developed the basic vehicle, what do we do so far as providing enroute therapeutic and educational enrichment?

Security and Therapy. A security stanchion is provided for wheelchairs, and an ambulator walker allows the youngster to stand or walk around in the vehicle. A fixed stand-up restraint system is also provided. By being able to stand or move his limbs he is promoting good blood flow.

Another most important spin-off we are developing is a restraint garment, which will have security harnesses that can attach at the shoulders and at the hip points to safely and comfortably keep the person in his seat during transportation. In our studies with the New York University Medical School, we have found that many of the short-stop accidents have actually caused damage to collarbones and other parts of the body under a sharp jolt. This restraint garment system will therefore allow G forces to be distributed over the whole body, and thus will greatly reduce injury. The rationale for all of the various systems I have described is to enhance therapy, to provide better control of emotional problems, and to also enhance education.

Educational Aids. One educational device is an auditory system that allows the youngster to obtain educational instruction from a tape the teacher has given him. A cassette loader makes it very easy for him to load and unload his educational material. Some educators and others have told us that to provide auditory and visual stimulation to a person in motion, especially a person with cerebral palsy, is going to be a bit of a problem. We have talked to many experts in the field and have found no one who can give us the answers we need to solve this particular problem. The planned vehicle test and evaluation program should provide valuable information in this area.

Figure 20-6 shows our classroom supplement. In this particular mode, the vehicle would be docked alongside a building, as an aircraft to a terminal. Students would come in and the teacher would teach right on board. This vehicle could be converted for many different types of therapy. In this case, the adjoining building would provide electrical power for air conditioning, lighting, heating, and educational devices.

Recreation Conversion

This vehicle is designed to be as convertible and as utilitarian as possible 365 days a year (Fig. 20-7). At the end of the school year, every device is removed from the inside of the vehicle except for the storage cabinet. Beds can be folded up against the wall, a toilet, a table, and cooking devices are provided, and the cabinet could be used to store clothing, food, and other paraphernalia. This vehicle could accommodate a group of handicapped persons on a trip for a weekend or longer.

This particular vehicle is in its final design stages and we anticipate having one available and driving on the streets of New York possibly by late spring or the early summer of 1972. It should be emphasized that the objective of all the analytical techniques and extensive analyses that have gone on over all these many months is to provide an end product that is adapted to the problems of the handicapped, rather than requiring the handicapped to solve their problems in the vehicle, and thus enable them to enjoy the same opportunities as any physically normal person.

VEHICLE CONTROL BY POSTURAL MOTION

Earlier work in this area was partly supported by NASA, and monitored here at the Ames Research Center by Mel Sadoff. The Grumman project deals with postural control of airborne vehicles. However, the relationship of postural control, in the sense used here, to problems of the mobility of the handicapped is clear.

The control system is being studied for both standing and sitting modes of operation and various degrees of freedom.

Various actions of the pilot in flying a helicopter have been simulated. Control of pitch, for example, might be achieved by tilting the upper body. Two-degree-of-freedom flight has been simulated with a relatively low frequency-response merely to demonstrate that the chair is not welded to the vehicle. In practice, a much higher gain and higher frequency are preferred.

It turns out that when you control a helicopter this way, you can almost bring a man in off the street and put him in there and have him fly the machine. This is because he is using torso motions that are *completely natural* responses to the dynamics of the vehicle. All control is achieved without the use of the hands, thus enabling the pilots or the drivers of vehicles to do other things than drive with their hands. We believe that with the human's precise control of the upper torso in 6-degrees-of-freedom by the legs and lower body, the hands and fingers should be reserved for more delicate operations than, for example, merely moving a control stick around. The pilot's chair also is counterbalanced by an air pressure device so that he needs to provide minimum body support. Note that the use of fore-and-aft and side-to-side sliding motions of the seat instead of tilting motions might be preferable for certain kinds of land-supported (as opposed to airborne) vehicles.

There are a number of applications of the concepts and technology outlined above. One is astronaut flight in vehicles from the lunar surface; NASA appears to have rejected this idea, but there are other space applications. Another possibility is the postural control of Army individual maneuvering units. Operation of a small one-man helicopter in this manner allows the pilot to use a laser designator, for example; this would never be possible in a small helicopter if the pilot's hands were occupied controlling the aircraft.

In explaining this concept in detail to people, we found that to counter the almost inevitable disbelief or a lack of understanding it would be helpful to construct a portable demonstration device that could be carried in the trunk of a car. A common reaction to parking lot demonstrations of the portable unit is "You know, that might make a nice wheelchair!" And, of course, the hands-free operation made possible by the postural control approach has obvious advantages for the handicapped individual who has lost the use of his upper extremities.

It should be emphasized that the portable unit is nothing more than an engineering, or a research, concept demonstrator–*not* a wheelchair, but a device to show the possibilities. Fore and aft body motions control the fore and aft velocity or acceleration of the vehicle, and differential body motions control turning–and at all times, the hands are free.

There are two modes that we see for a real wheelchair based on this concept. One we call a "wagon mode," with a wheel in front, where the center of gravity is in general supported in a regular wheelchair manner. The other is the "balance mode," which results in what we call the "Smoky Stover cart." (Any of you who have followed the comic strips will know what we mean by that.) There are only two wheels, yet one can balance the unit with no problem whatever by postural control. And the advantage of the balance mode would be a considerably greater agility, since it would probably pick up higher performance and have a smaller footprint on the ground.

DISCUSSION

Questions on the Four-Wheeled Vehicle Transportation System

Q. You showed your transportation device in terms of a systems design approach, and really what you talked about seems to be the vehicle–I mean the system in terms of the vehicular system concept. Did you study the overall or economic system concept? For example, it seems that the vehicle as sketched would hold four or at most six and yet would require a staff of two.

A. It may only require a staff of one. However, during our test and evaluation program we are going to be looking at this. UCP of New York City requested a vehicle to accommodate six people, but larger capacity vehicles are available.

Q. You seem to imply a driver and instructional assistant.

A. There conceivably could be an instructional assistant, but if instruction material were prepared in advance at the school, the driver would just need to insert it in the various instructional devices.

Q. Earlier in the day there was reference made, I guess by Bliss (Chap. 16), to the problem of carrying the product finally to the community, the user. Your vehicle is beautiful but may be a little too fancy or too beautiful. Is your study also trying to look at how such a system could be economically justified or brought to fruition as more than sort of a technical concept?

A. Well, we are working with the Bureau of Handicapped Children for HEW, and we have shown them this concept. They have asked us to prepare a demonstration for them. And this first vehicle will actually be a demonstrator vehicle prototype. We will be starting probably in the spring of 1972. They have indicated that they would like to be able to have vehicles of this type made available for every school district in the United States that transports the handicapped. This vehicle, with its full 365-day utilization, is designed to be cost-effective.

Q. The cost may actually turn out to be less than the current cost for providing teaching in the home?

A. Yes. In fact, I am glad you mentioned that. One of the questions raised by people at HEW was the possibility of applying the cost in the educational day, instead of beginning at the time a youngster gets to school, to transportation and education while in transit, and if this is the case, which they strongly feel will be, it will actually possibly be cheaper in the long run to perform education.

Q. You mention that the seats were facing forward for safety purposes. Why is that?

A. We have also looked at rear facing seats, by the way, which many people say are supposedly safer, but public acceptance of rear facing seating has been very difficult. And one consideration is acceptance of the product by the user. There have been many studies on side-facing seating, forward-facing seating, and rear-facing seating.

Q. I think this was a great idea. I do hope, however, that the impression is not conveyed that this is the first time that there has been a thought of involving education with a trip to school—because that is not a new concept.

A. No, we never intended that it should be considered as a new idea in education.

Q. School systems have been using the bus ride for educational purposes for a while.

A. Yes, but not in this context, with its multimode capabilities.

Q. It looks like an Econoline chassis. Can you tell me what kind of——?

A. Actually, the vehicle has a front engine, front wheel drive with a low chassis. In this vehicle, a person 6 feet 4 inches tall can stand up, whereas in an Econoline you can't stand up at all if you are over 4 feet tall. The vehicle is 21 feet long by 8 feet high, and 8 feet wide.

Q. You are scratch-building this thing, you are not buying a chassis and modifying it, is that correct?

A. We are buying an engine, transmission, and basic chassis, and are building everything else, including the body and everything else in the interior.

Questions on Postural Control

Q. I would imagine when you are sitting on the seat which you push up and down and side to side in a real helicopter or a real aircraft, the inertial characteristics would be hard to scrub out.

A. No, as a matter of fact, they are helpful, because the kind of control that you have is inherently negative feedback so that your body tends to be inertially stabilized just by its mass. If you didn't do anything about moving your body, the feedback is such as to correct disturbances that might come about.

Q. It could be arranged with a clutch, though?

A. But it wouldn't work.

Q. Suppose you are going forward like this and you want to stop, you move back, don't you?

A. That's right.

Q. Doesn't your inertia throw you forward again?

A. No, the vehicle follows you. When you lean back, the vehicle leans back.

Q. Sure, but suppose you try to lean back and the vehicle follows and stops?

A. No, it doesn't stop unless you stop.

Q. It is under-critical damping, so that––

A. No, that's not really crucial.

Q. I am just offering an independent opinion. We have been working on similar sorts of things, and it does work just as you describe, and the inertial forces are in a direct––

Jones: But you still have dynamics to contend with.

A. Yes, but there are some strange things about it, too. You have to adjust things in a very unusual manner, but you end up with a very nice system.

Jones: I think the really important thing to emphasize is that it is not so much that a new gadget is devised, but that it exploits our built-in aptitudes–rather than requiring coded information in the instruments and reflexes that you have never used in your life before.

A. Right.

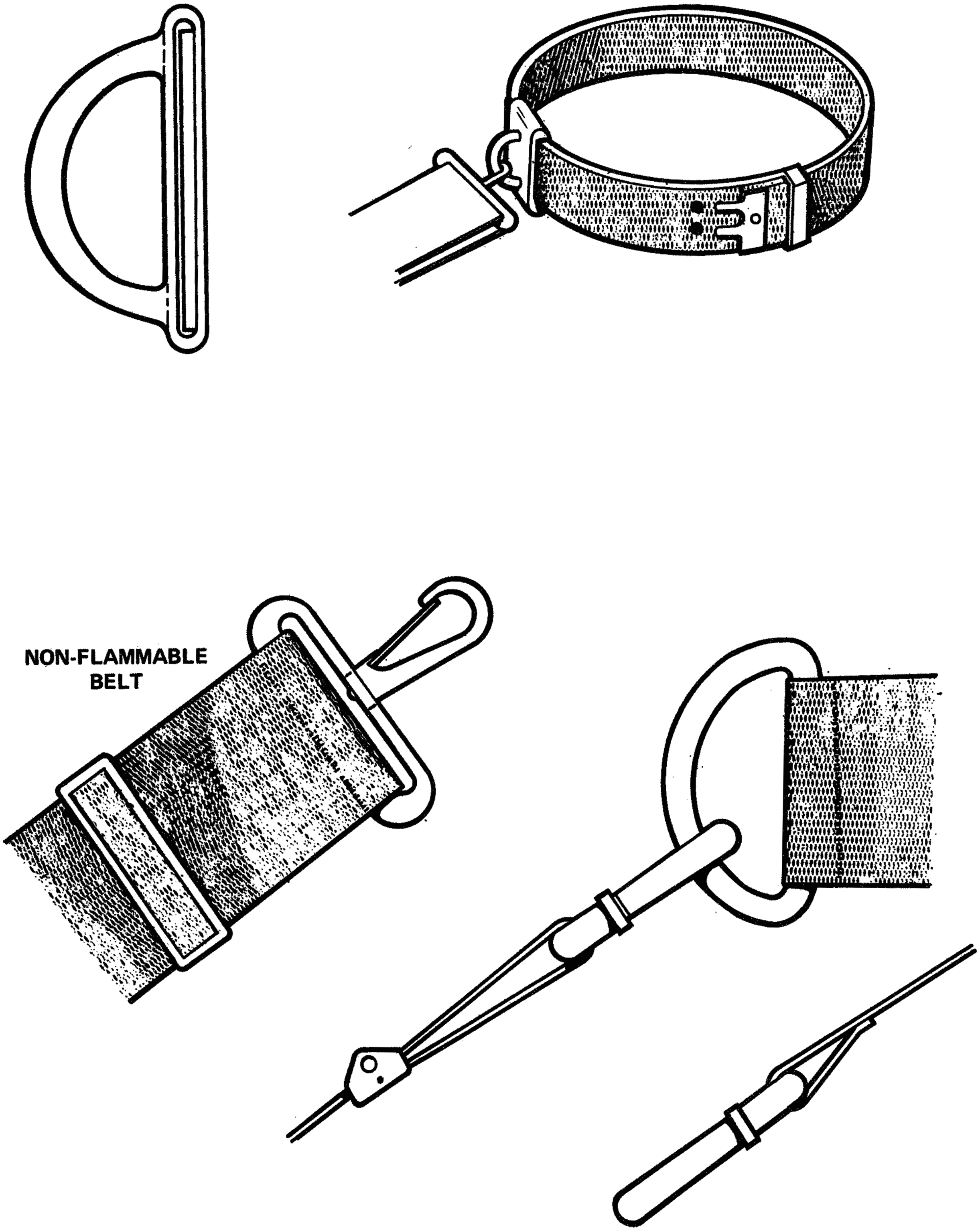

Fig. 20-1.– Wrist tether belt and flexible waist tether.

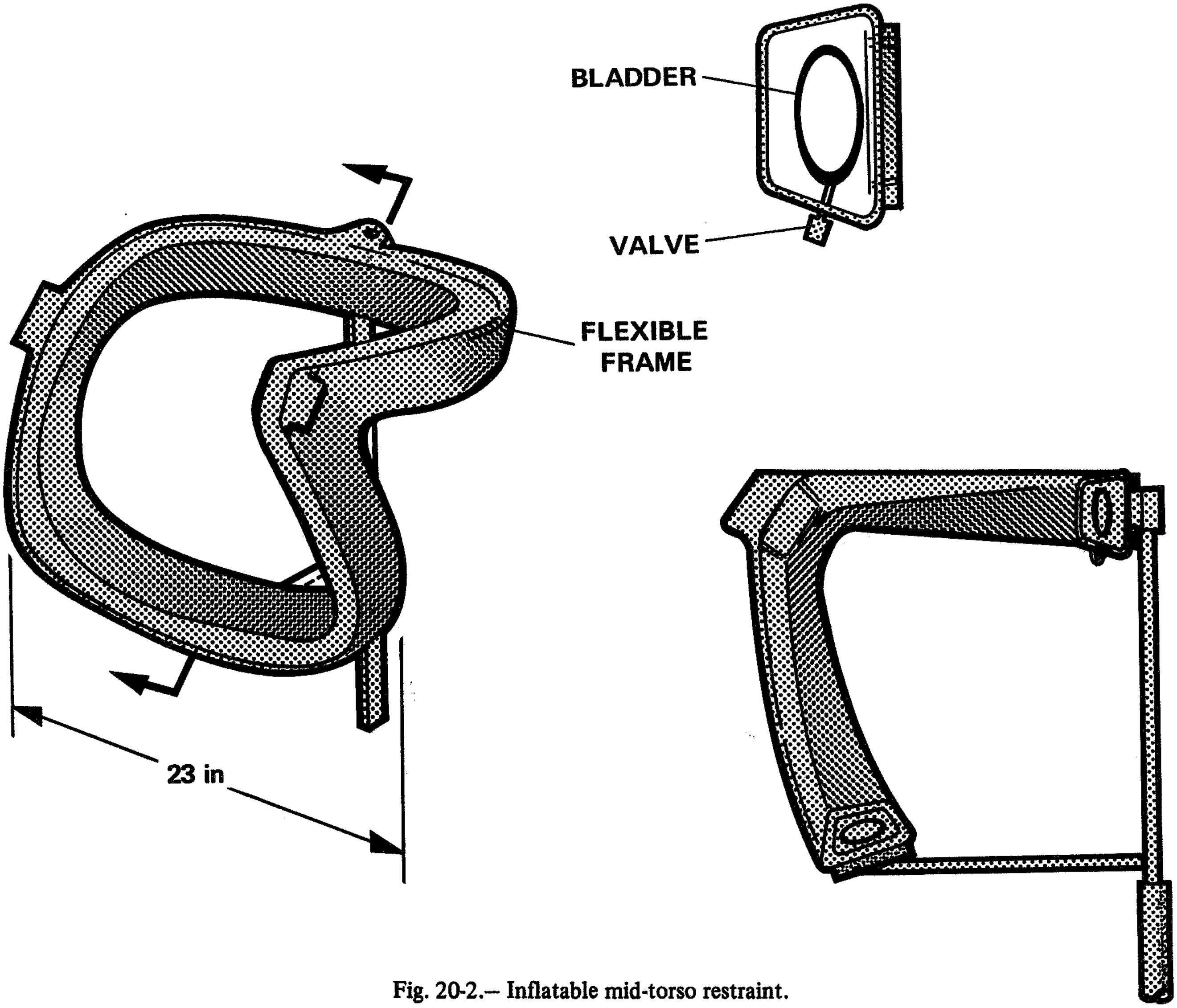

Fig. 20-2.– Inflatable mid-torso restraint.

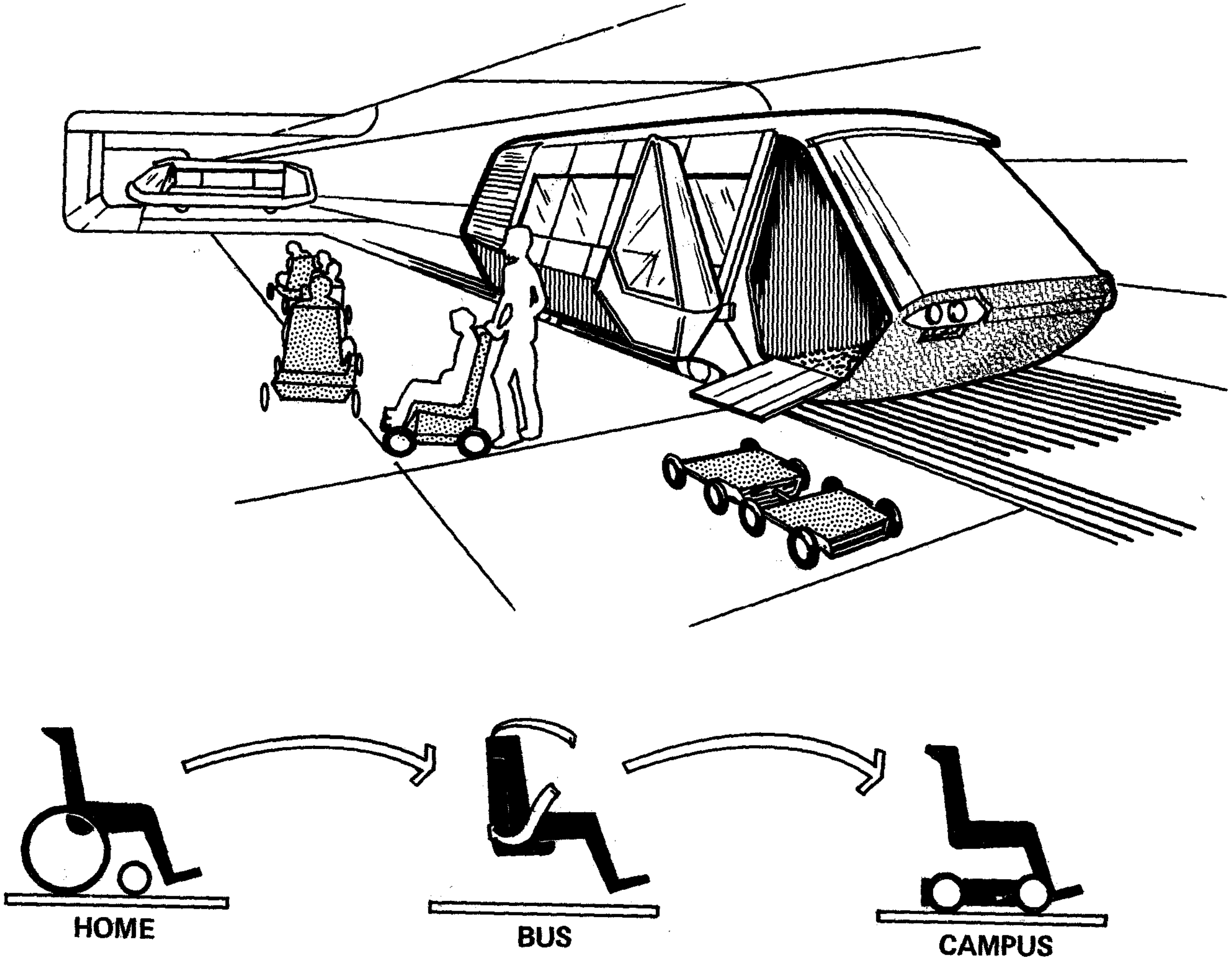

Fig. 20-3.— The wheelchairs train concept.

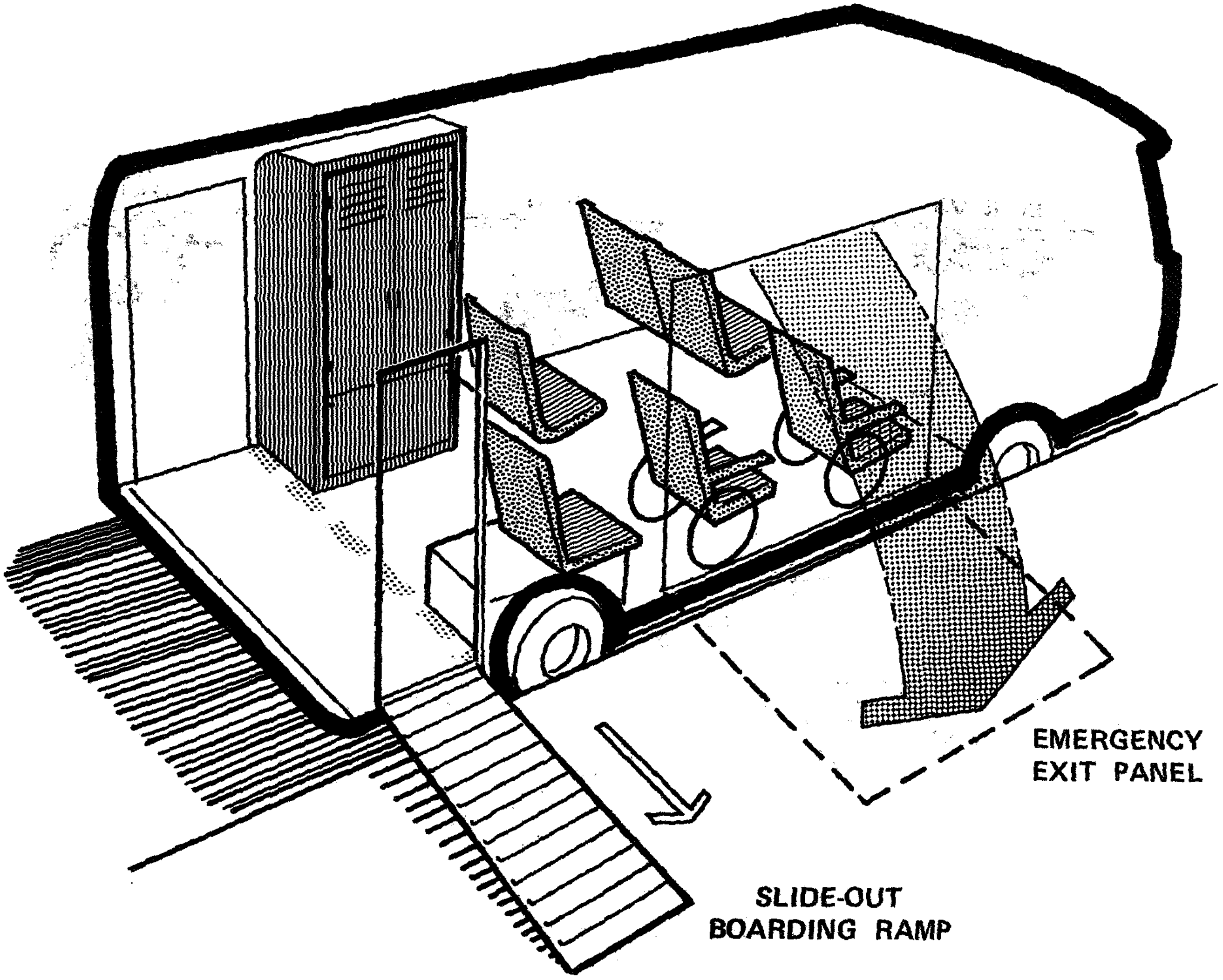

Fig. 20-4.— Basic vehicle design.

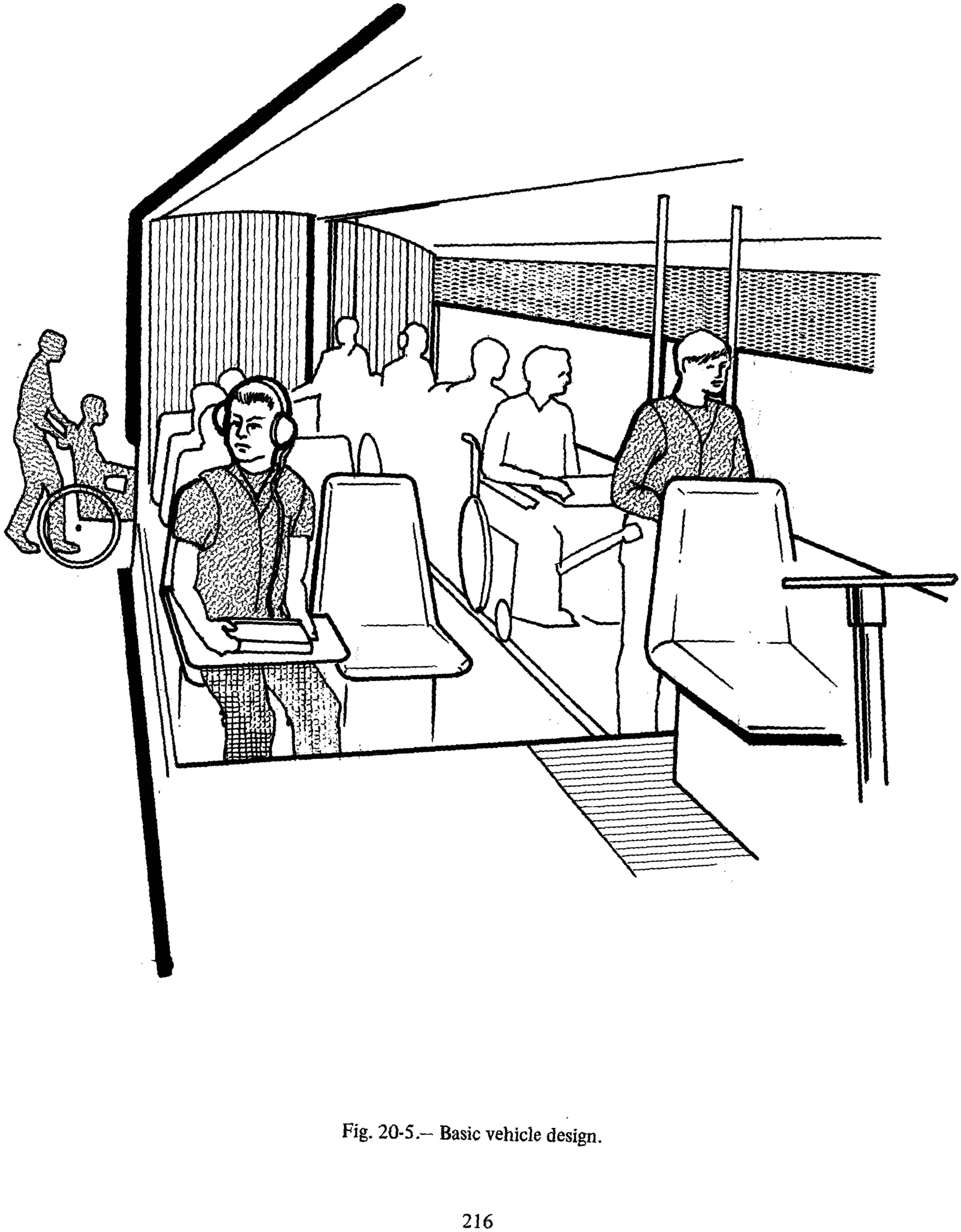

Fig. 20-5.– Basic vehicle design.

Fig. 20-6.– Classroom supplement.

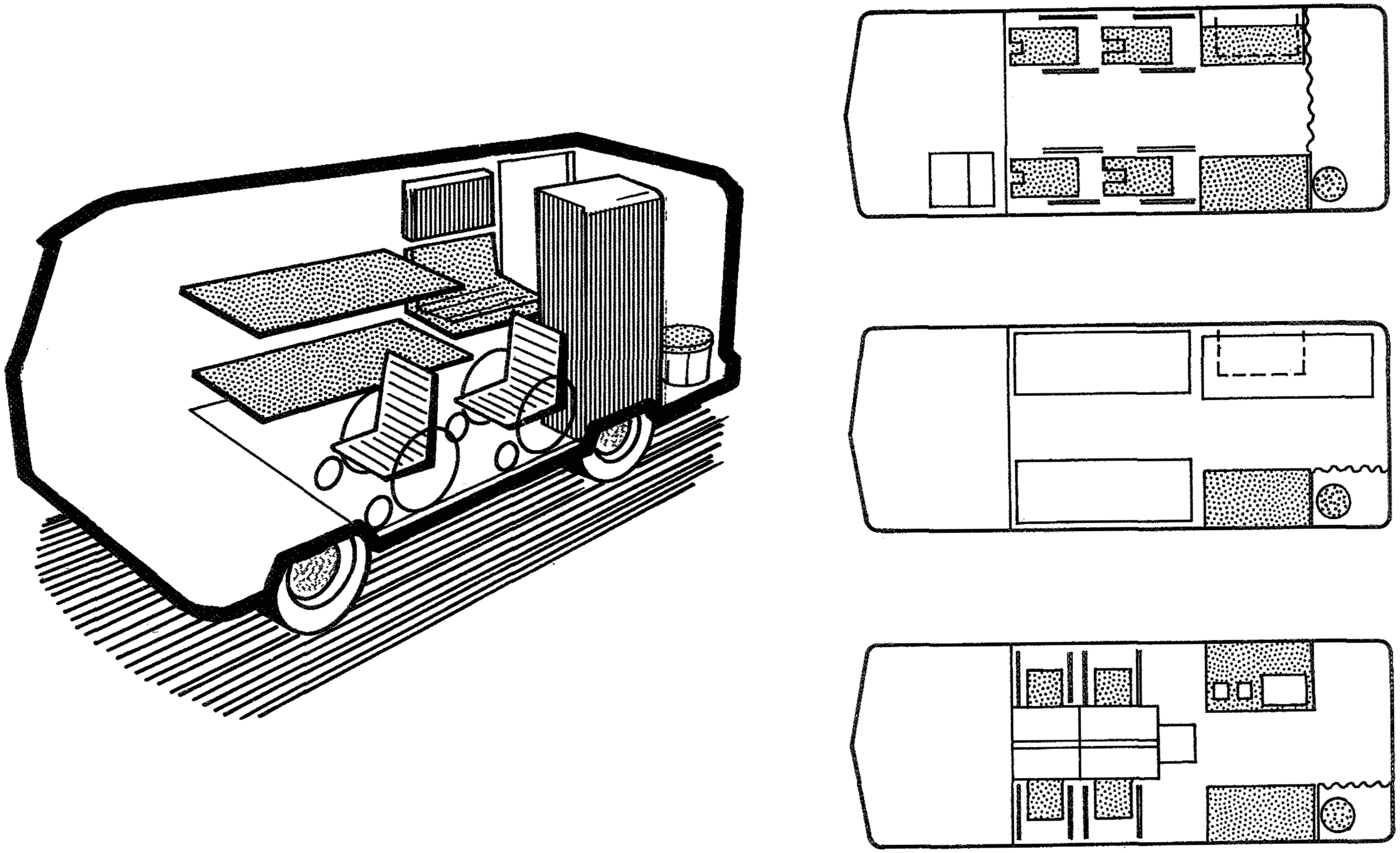

Fig. 20-7.– Summer recreation conversion.

Chapter 21

CYBERNETIC ANTHROPOMORPHIC MACHINE SYSTEMS

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Mechanization Systems Section
General Electric Company

The Cybernetics Automation and Mechanization Systems Section of GE is interested primarily in the hardware aspects of machinery and equipment—termed *cybernetic anthropomorphous machine systems* (CAMS)— developed for applications entirely different from those of aiding the neurologically handicapped. CAMS have been used primarily to augment the capacity of normal humans in three areas: strength, reach or physical size, and environmental interaction. It is apparent that applications to the problems of the handicapped are possible, and should be explored.

This chapter provides a functional description of some of the CAMS developed or under study by the GE group. Examples are shown in Figures 21-1 through 21-3. The first is a research test bed of a four-legged walking vehicle—a space manipulator vehicle that could be operated from an associated manned satellite or from Earth.

Figure 21-2 shows an underwater research submarine with a set of manipulator arms attached to it, and Figure 21-3 shows a research prototype of an exoskeletal arm capable of lifting 750 lb.

The term *CAMS* has been used for about 10 years; it well describes the work in which we are involved, and corresponds to Mann's description of cybernetics as well (Chap. 13). As shown in Figure 21-4, the human operator is included in the loop, and the machines we deal with are anthropomorphous or man-like in form to a greater or lesser degree. The man-machine interface has been the subject of the greatest amount of effort, but the machine-computer interface and some hybrid systems combining man, machine, and computer have been studied as well. Our work in the computer control of these machines is very much in the preliminary stages, but our concepts of possible adaptations of this hardware to problems of the handicapped suggest the use of computer control schemes, very possibly time-shared computers, to get the programming function to an acceptable economic level.

CONTROL TECHNIQUES

Instinctive Control

The man-machine relationship is illustrated by the master-slave machine in Figure 21-5, the first of the CAMS-type machines, which was built some 12 to 15 years ago. This machine was developed by Mr. Ralph Mosher, formerly associated with General Electric, for use in a nuclear facility. It is electrohydraulic with electrical cables connecting the master and the slave. The slave arms are anthropomorphic. In discussing our control technique, we refer to *spatial correspondence*, or *mimic control*, between the master and slave. On the machine shown, the multiple degrees of freedom of the slave arm are controlled by the operator carrying the master through motions that are normal or reflexive to him. *Instinctive control* is another term we have applied to this type of machine. The operator can control multiple degrees of freedom and whirl a hula hoop as shown. To effectively whirl a hula hoop or a device of high inertia required additional input, provided by bilateral servos and force feedback, to the mimic type motion—a "feel for the inertia"—to permit introduction of the acceleration effects at the proper time. In the case of the master control, for example, actuators are provided at each of the degrees of freedom so that a proportion of the force felt by the slave can be fed back to the master. (A bilateral servo is one that can be operated from either end with force proportionality.) If, for example, there is a 5-to-1 force ratio between the two, in operating the machine from the slave end, exertion of 5 lb would yield 1 lb at the master, or vice versa.

Figure 21-6 shows a machine that is in commercial production by General Electric and is used in industry. This is also a master-slave device.

These machines demonstrate the possibilities of reducing a fairly sophisticated technology to simple hardware that is economic and reliable. Growing acceptance of these devices in industry is an indication of the direction that these developments can go under appropriate circumstances. The operator is seated and grasps a master control with a handgrip that is moved in natural arm motions and is mimicked by the large slave arm. The arms are made in three sizes with reach capabilities out to perhaps 20 ft and load ranges from 100 to 1,000 lb.

Computer Control

The control technique outlined above has limitations in possible applications for the neurologically handicapped, and as noted, computer control schemes appear more promising. In the schematic of Figure 21-7, the boom, or arm, is controlled by a computer through suitable interface electronics. The programming of the computer can be accomplished by a teletype or other suitable means, or it can be taught through the use of some form of a teach station, as shown in Figure 21-8. An industrial computer is shown, along with the interface electronics and a conventional teletype station. We use the master control as the teach station, run the computer along with it, go through the memorization function, and then go to a playback mode. Once the computer is programmed in, it is possible to place subroutines on the computer and make selective modifications of that program. For example, we can put in override control that will change the position gain or the time gain or other similar factors. This feature may have some significance to the problems of the neurologically handicapped.

Some years ago, we coined the term *mechanism cybernetics* because none of the conventional disciplines seemed to cover the mix of disciplines involved in making effective devices of the type described here. In general, an expert in mechanisms must have a considerable degree of competency in all the fields indicated in Figure 21-9.

SOME CAMS FUNCTIONS

Exoskeletal Devices

Figure 21-10 is an artist's concept of the exoskeletal arm.* The operator dons an external skeleton and becomes, in effect, a walking forklift truck. The design capability is 1500 lb of lift. The significant concepts of this machine are in the points of attachment, and the natural way in which it is controlled, much as is true of the types of devices built by Grumman. In this case, the operator uses a ski-boot type of

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*Funded by the Office of Naval Research and the Army.

attachment at the foot and a simple belt around the waist, so the attachment at these points permits control of the walking mode. He thrusts his arms within the master control, which has a ring restraint about the arm and a handgrip grasp permitting a combination of a pseudoprehensile grasp and the introduction of a moment for control of the machine.

The concept makes a very compact and interesting device but constructing it is extremely difficult, from a servo and mechanical design standpoint. It is a coaxial device, which means that if you have a forearm rotation motion, for example, the center line of the operator's arm and the master into which he puts the signals must be in line, so that they are coaxial. We then must add a coaxial 750-lb slave, which must follow the master. Then we add an elbow, necessitating a change of axis, and it still all has to be coaxial. This is where you get into the fun of the design and the controls of this kind of device.

Other exoskeletal work involved potentiometers placed on the various joints and tied to computers to objectively measure the range of motions of such devices during walking, crawling, creeping, climbing, and similar activities. Figure 21-11 shows a device designed for an atrophied limb; the machine dynamically counterbalances the weight of the extremity.

Some work done with the Marquette Dental School involves measurement of the jaw motions under varying bite conditions. The potentiometer in Figure 21-12 is tied into a computer analysis scheme.

Figure 21-13 shows a prosthesis developed with the University of Virginia and VRA, four or five years ago. This is a power augmentation scheme that used the residual power of the operator, a battery pack, motorized hydraulic pump, and miniaturized hydraulic components for weight response and low-noise emphasis. It did have some force "feel" with it. Figure 21-14 shows use of the prosthesis by an amputee who found it to be very, very effective as compared to the Bowden cable type of approach.

Quadruped Vehicle

The mode of control of this machine is shown in Figure 21-15. The two hands control the front legs, the two feet control the rear legs. For safety reasons, an overhead tether is provided, but it is relayed so that the machine operates under its own impetus motion. The design objective was to develop the technology and demonstrate the instinctive control capabilities. The sense of feel the operator has with this machine affords him perfect control and knowledge of the stability of the situation.

The vehicle is very limited in its walking function, but it was intended that way. To illustrate, there are three degrees of freedom in each leg. In the hip, there is an abduction-adduction motion, a pivot, and a knee motion. By comparison, the human has 8 degrees of freedom in his leg and three in his pelvis and hence uses 11 degrees of freedom for the walk mode. Compared with the walk mode of a horse or an elephant, that of the vehicle shown is relatively crude, but its real significance lies in the versatility of its control capability, even with its limited walking function.

Industrial Master-Slave

Figure 21-16 shows the "in-factory" usage of an industrial machine of the master-slave type. The machine shown is being used at an appliance factory to dip a dryer drum and washer body in a paint bath.

Other machines of this type have a telescoping arm or articulated elbow joint. As with other "instinctive control" devices the significant feature is the force feedback, which affords the operator a fairly sensitive indicator of the appropriate degree of motion, grasp, or other control for the task at hand.

Space Maintenance System

The space maintenance system shown in Figure 21-17 is a man-equivalent type of device. It is a radio-dispatched repairman in space, who, in this case, is replacing an electronic module. Figure 21-18 shows a manipulator simulation in the laboratory using the same type of equipment.

Communications

Figure 21-19 shows a blind-deaf communicator which breaks down audible speech into some 44 major components and provides the information to the operator by means of electrically actuated stimulator pins.

IMPLICATIONS FOR THE NEUROLOGICALLY HANDICAPPED

In terms of aiding the neurologically handicapped, CAMS technology as it has been developed for the major applications outlined here appears adequate in some areas and limited in others. The former include basic machine design, kinematics, servos, and the physical interface of man and machine. Further development is needed in such areas as control, which in the case of CAMS is primarily the "instinctive control" based on force feedback and geared to the capabilities of normal humans; the development of computer control schemes thus is indicated. An associated area is that of the man-machine control interface. A systems approach and studies of human factors similarly require further attention. A particularly difficult problem lies in the availability of miniaturized components for the human patient.

There has been considerable discussion (Chaps. 13 and 14) about what to do next—what is the best approach to applying technological advances to the problems of the handicapped. There is much interest in the differences between the detailed systems approach and the free-wheeling development team approach. It appears that the free- wheeling development team might offer a great deal in this case. Certainly, it is a great means of motivation, and if more than one team is put together in competition, that can provide additional motivation as well. I think the most difficult problems involved in moving forward are in the conceptual definition of a suitable mission, as outlined so effectively by Mann (Chap. 13): the mission must be specific, it must be simple, and it must be understandable. In this field, it is not easy to set such goals.

DISCUSSION

Q. There seems to be an inherent assumption that it is better if the driver of the prosthesis or the anthropomorphous artificial arm is encased in the arm itself. I guess I am questioning that assumption. It means in your case that there could be some risks in having this guy in the exoskeletal——

A. Yes, well, this was in large part dictated in this case by the sponsoring group, experts in human factors, who felt strongly that the operator should be right there so that he can smell and taste and feel and have the most intimate visual feedback as well as force feedback. These were the guiding considerations. It is, I think, a subjective tradeoff as to whether this should be done or not.

Q. The point is, of course, he could be right there but two feet away and still smell, taste, and feel but not be subject to the thing when it——

A. That is right, and it would be possible to avoid some of the complexities of the walk mode. I think there was a strong input from the human factors area that the project be set up to find out what the effects of these things would be. So it has been our basic assumption that it would be done in this fashion.

Q. Are we going to see one soon?

A. The machine is essentially complete at the present time. We have done some testing on the complete machine which is very encouraging but preliminary. I think subject to the wishes of our sponsors, perhaps in another six months or so, there may be considerable more information available on it.

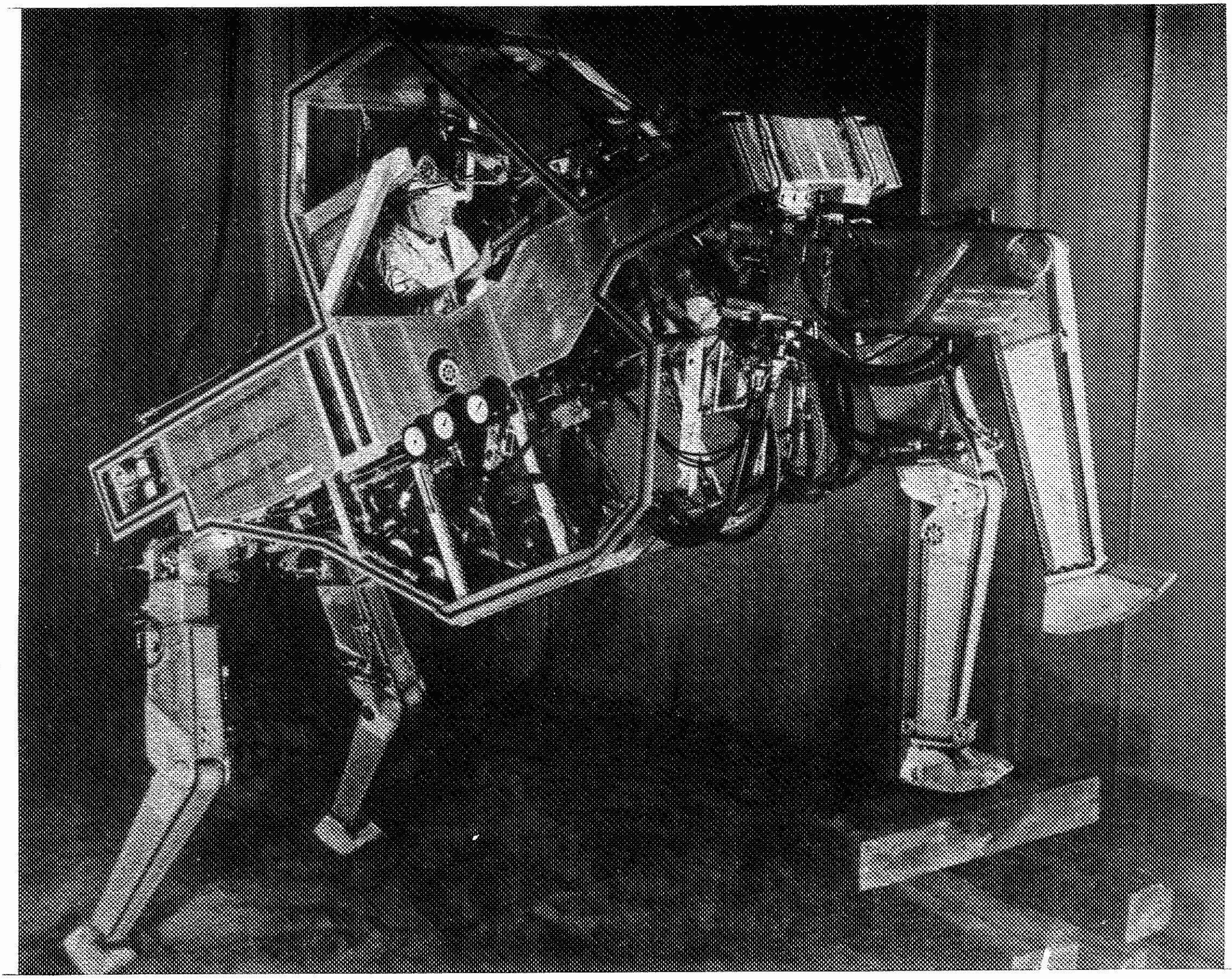

Fig. 21-1.– Four-legged walking vehicle.

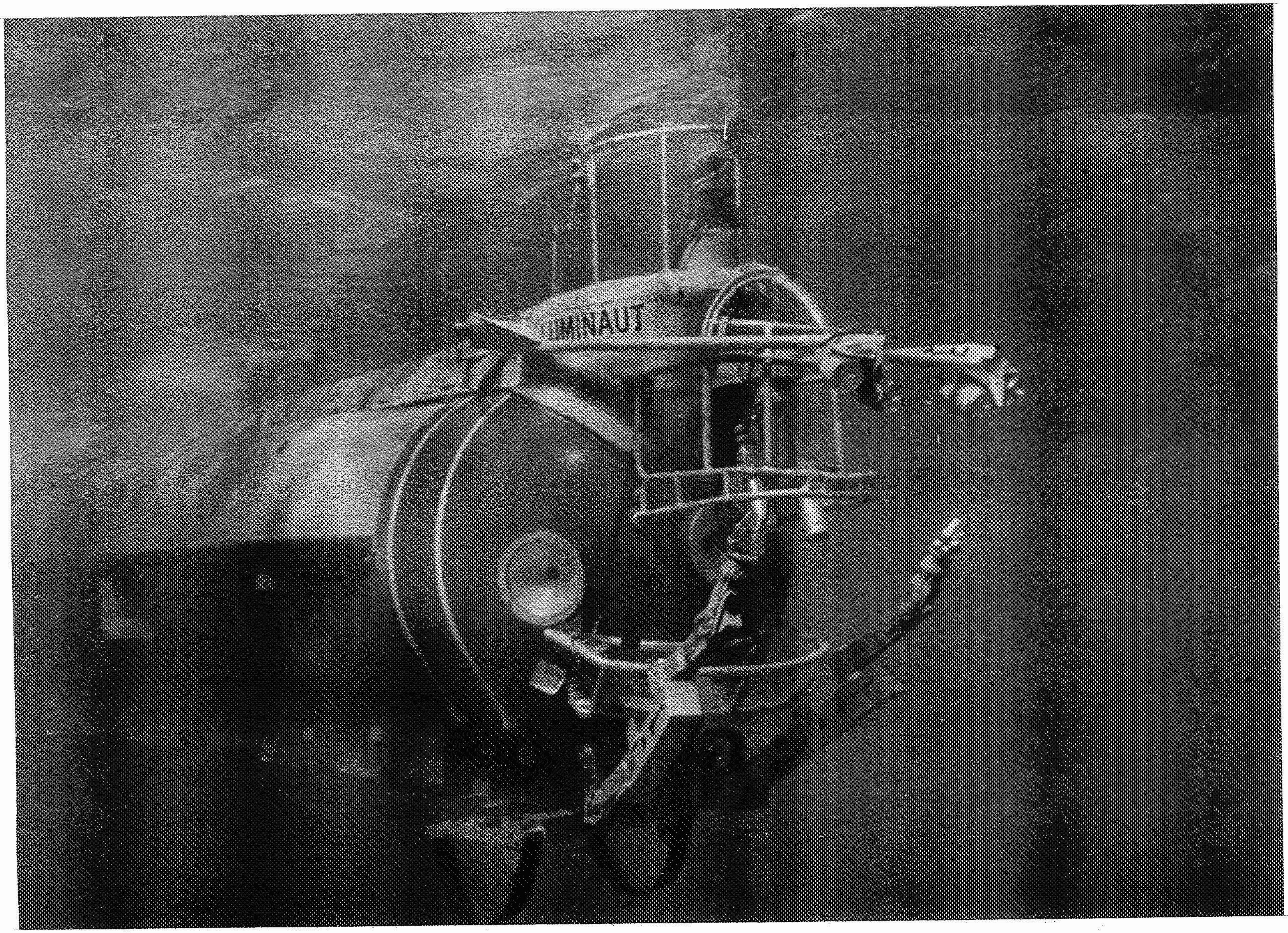

Fig. 21-2.– Underwater research submarine with manipulator arms.

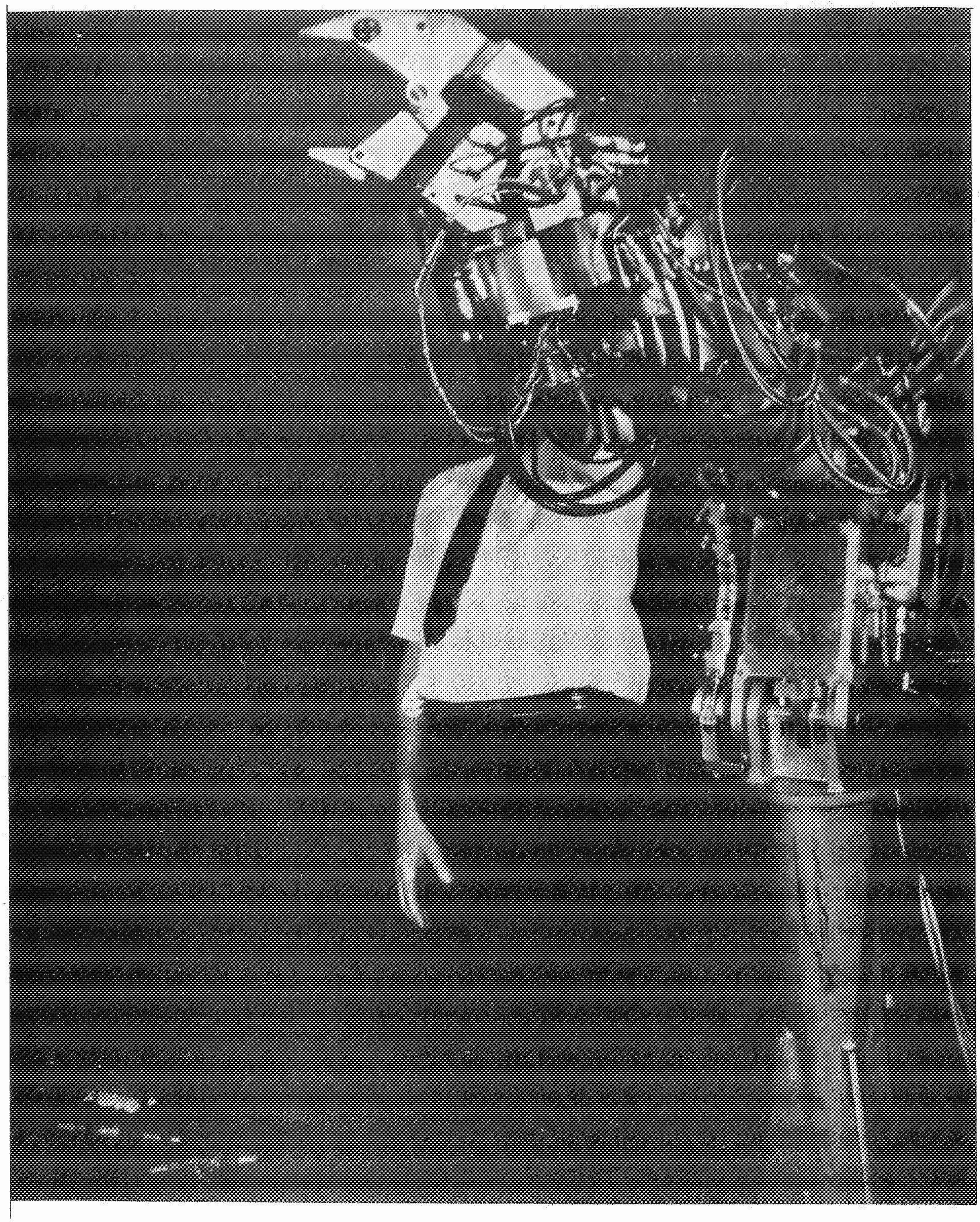

Fig. 21-3.– Research prototype of exoskeletal arm capable of lifting 750 pounds.

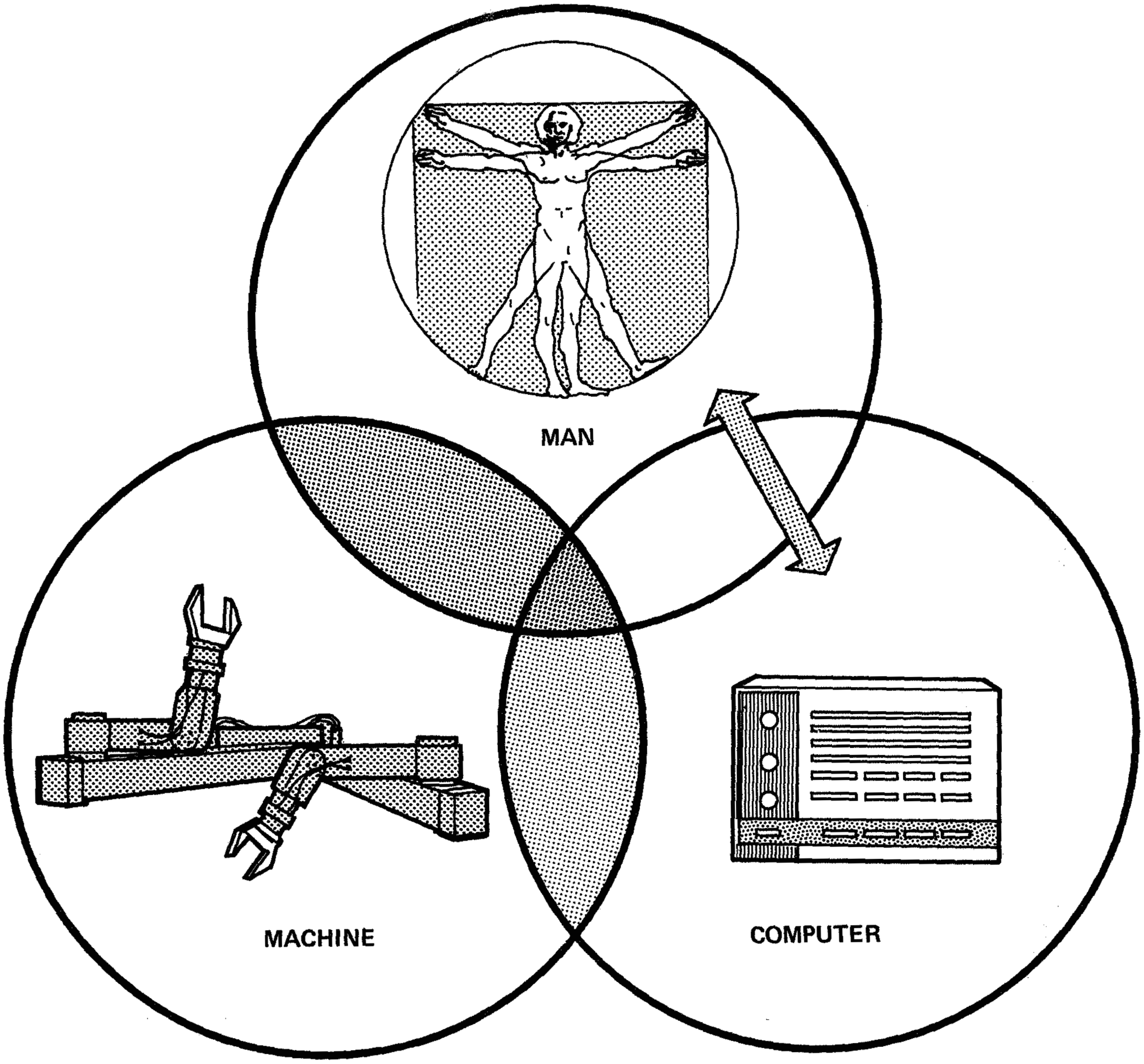

Fig. 21-4.– The CAMS arena.

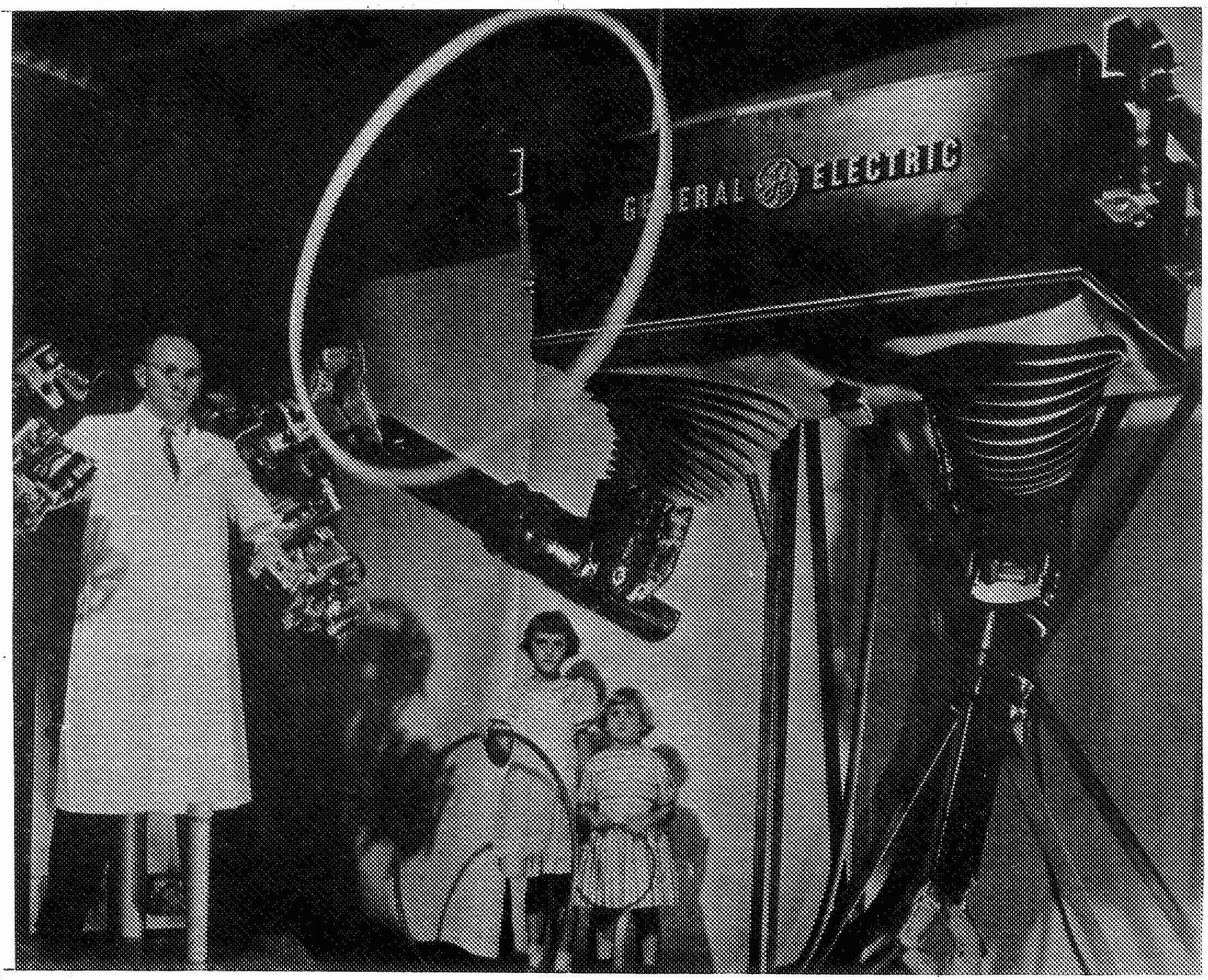

Fig. 21-5.– Master-slave machine, the first CAMS type device.

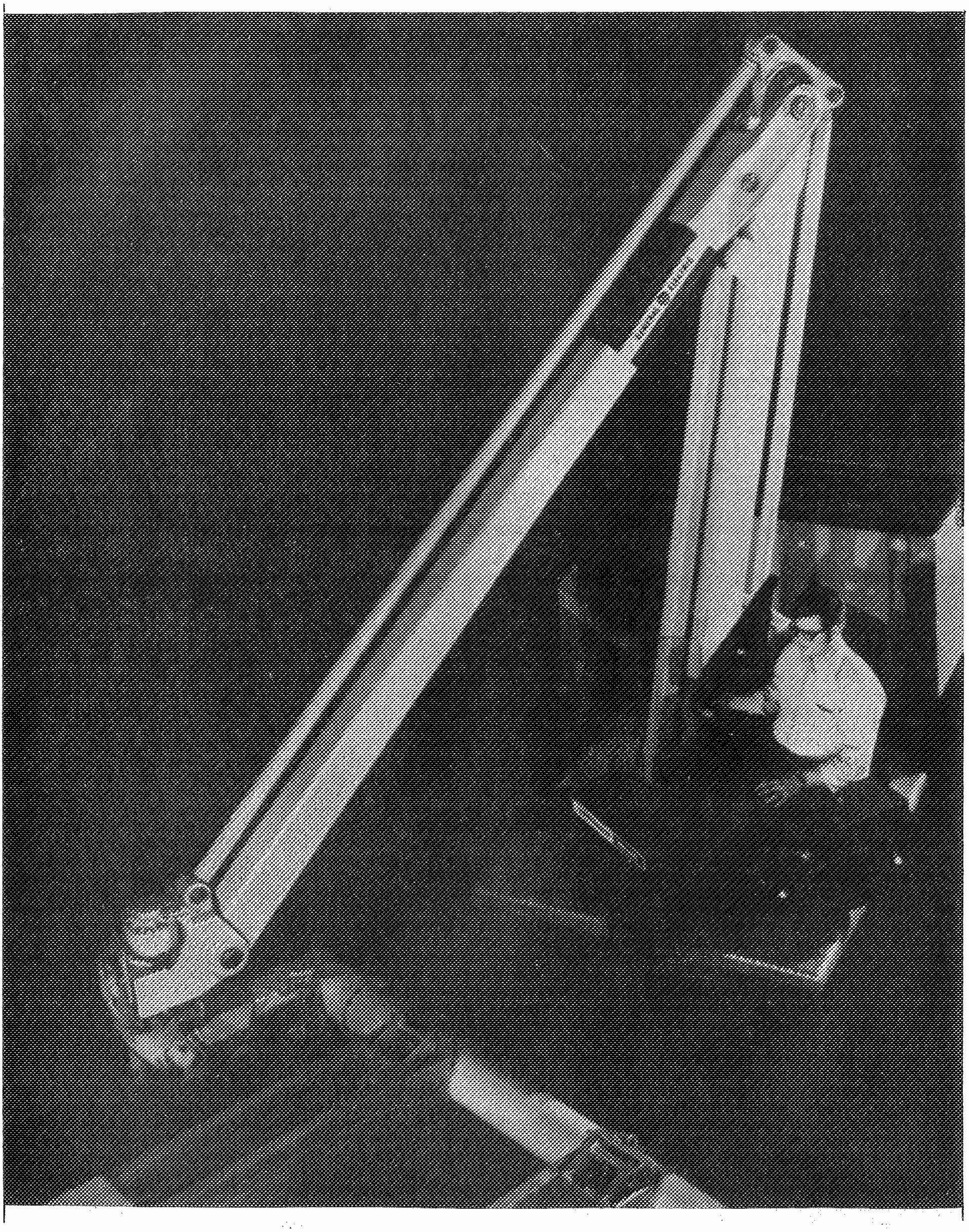

Fig. 21-6.— A master-slave device that is in commercial production; available capabilities are a reach of up to 20 ft and lift of 100 to 1,000 lb.

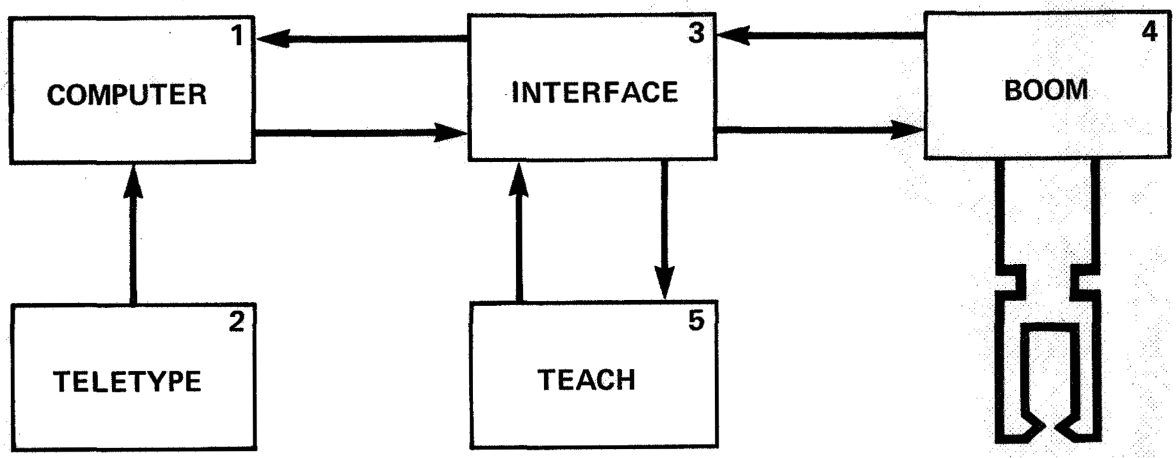

Fig. 21-7.– Computer-mate schematic.

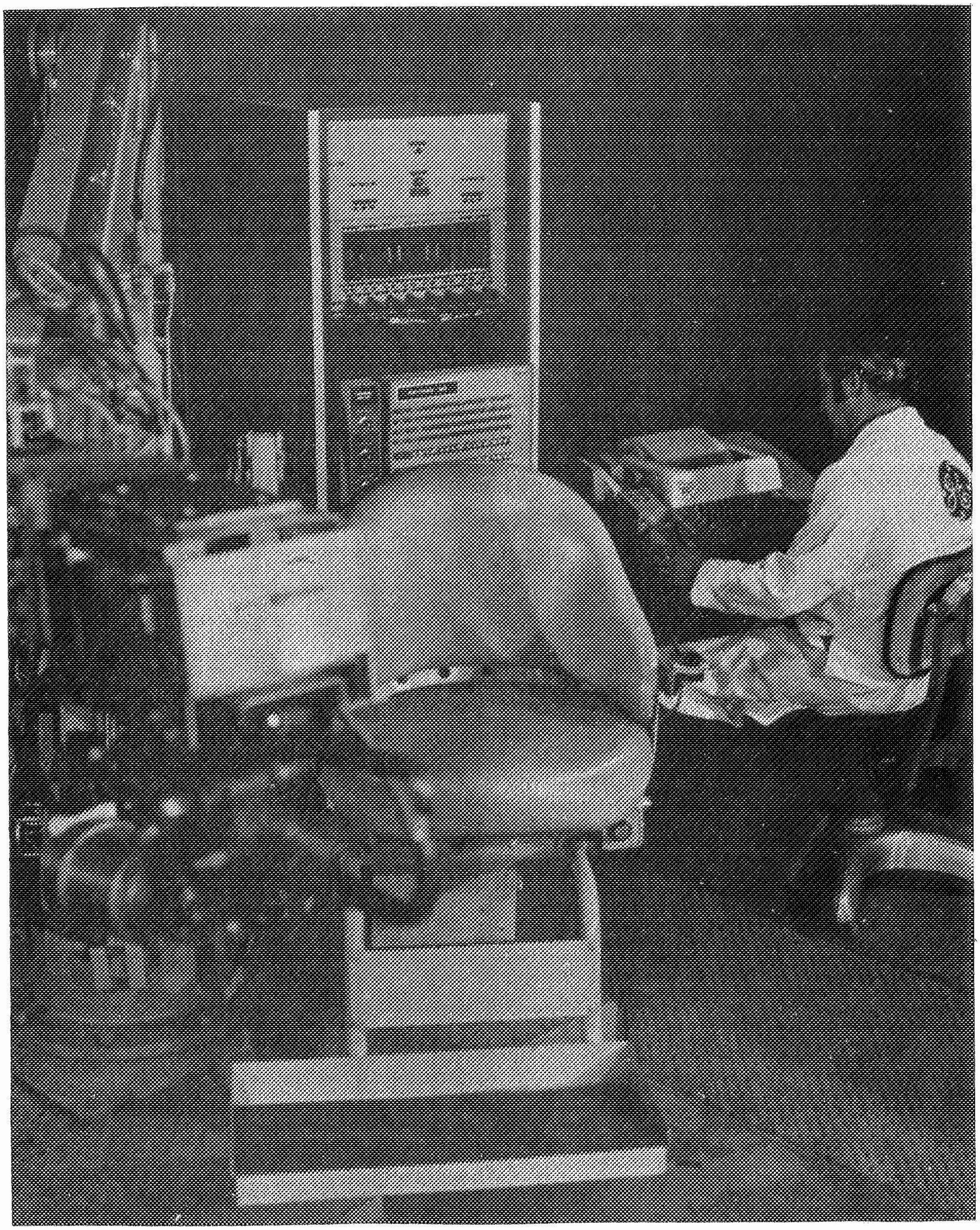

Fig. 21-8.– Computer programming through teach station.

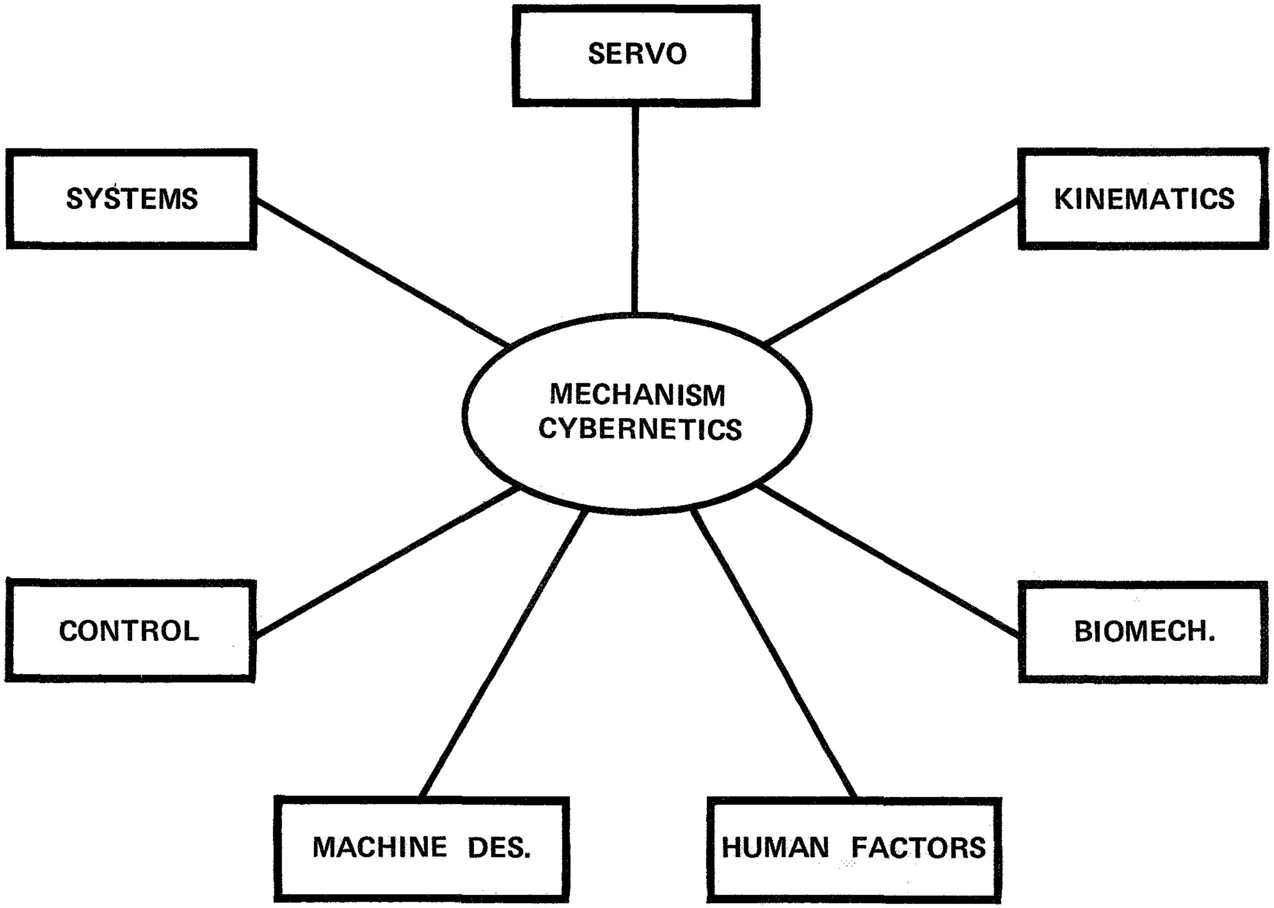

Fig. 21-9.– The technology mechanism cybernetics.

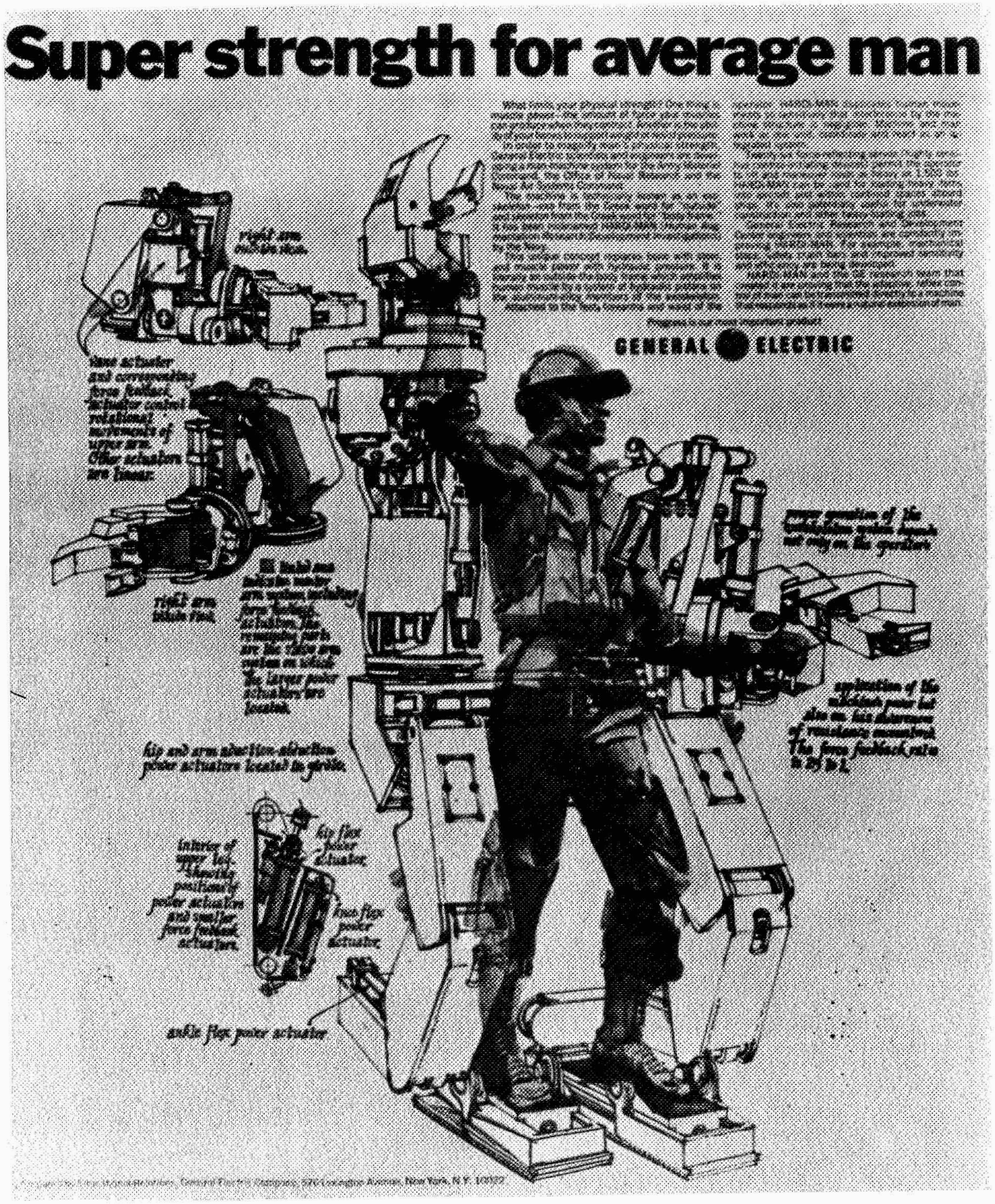

Fig. 21-10.– Exoskeleton for lifting and maneuvering up to 1500 lb.

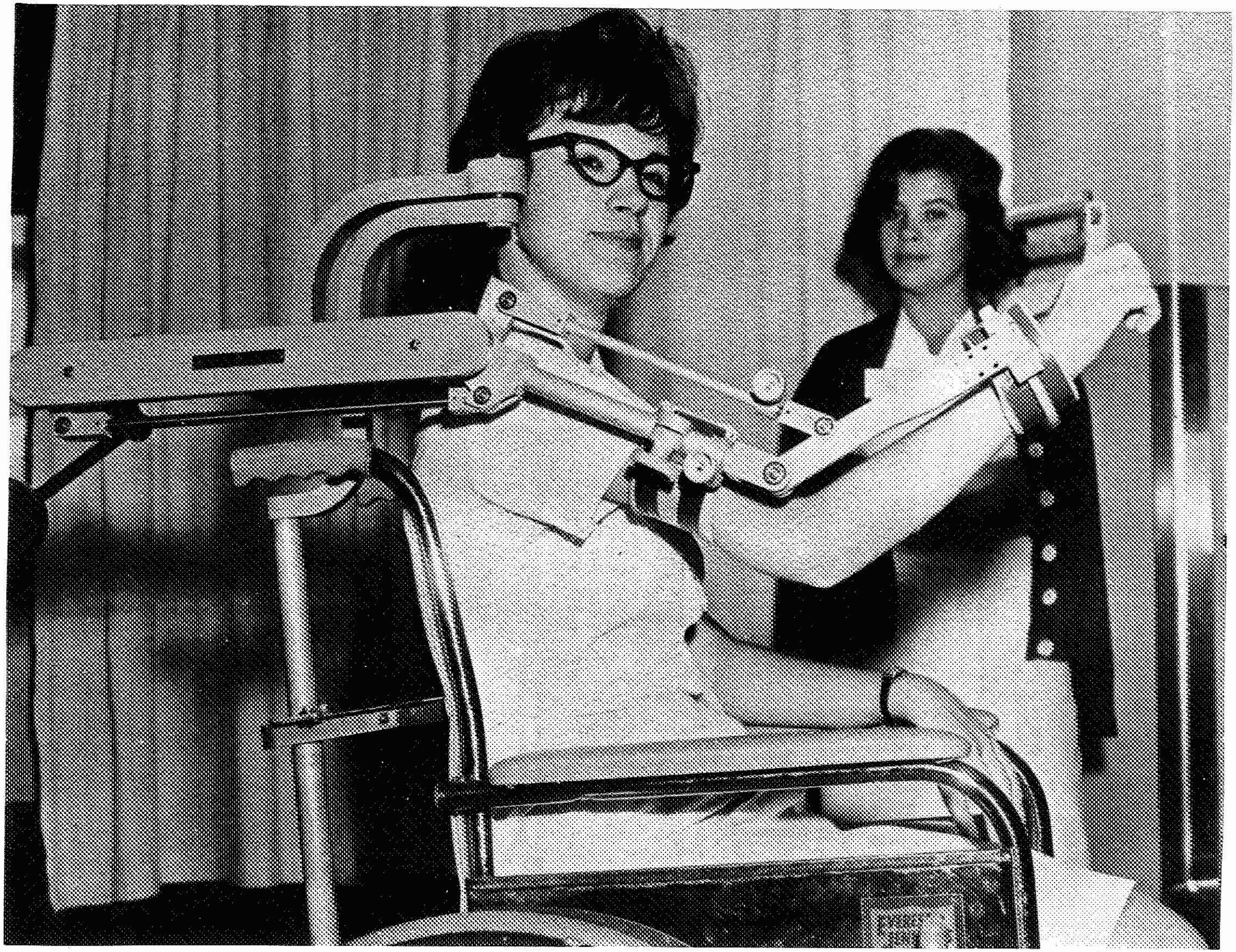

Fig. 21-11.– Exoskeletal device for an atrophied limb.

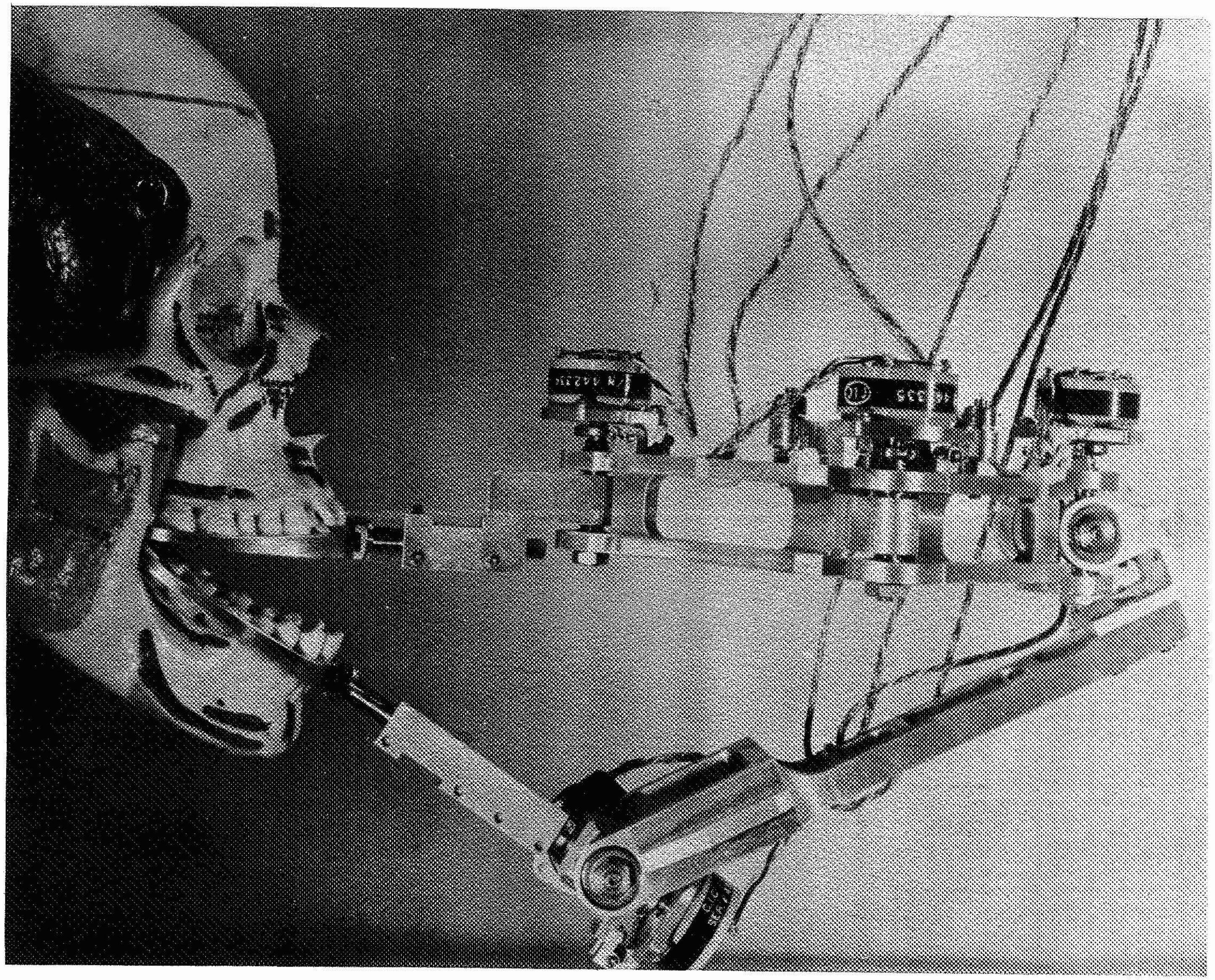

Fig. 21-12.– Device for measurement of jaw motions.

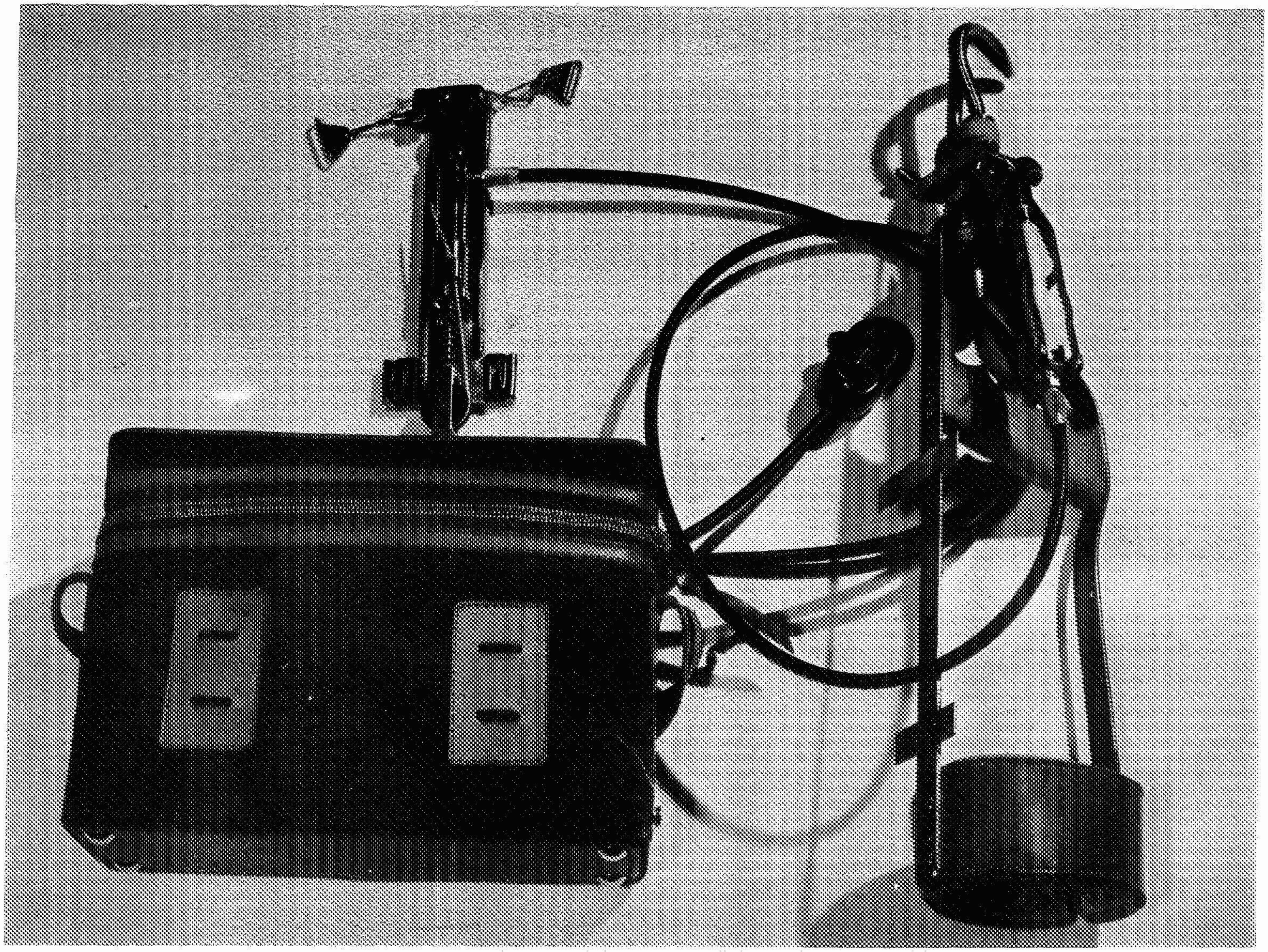

Fig. 21-13.– Upper extremity prosthesis.

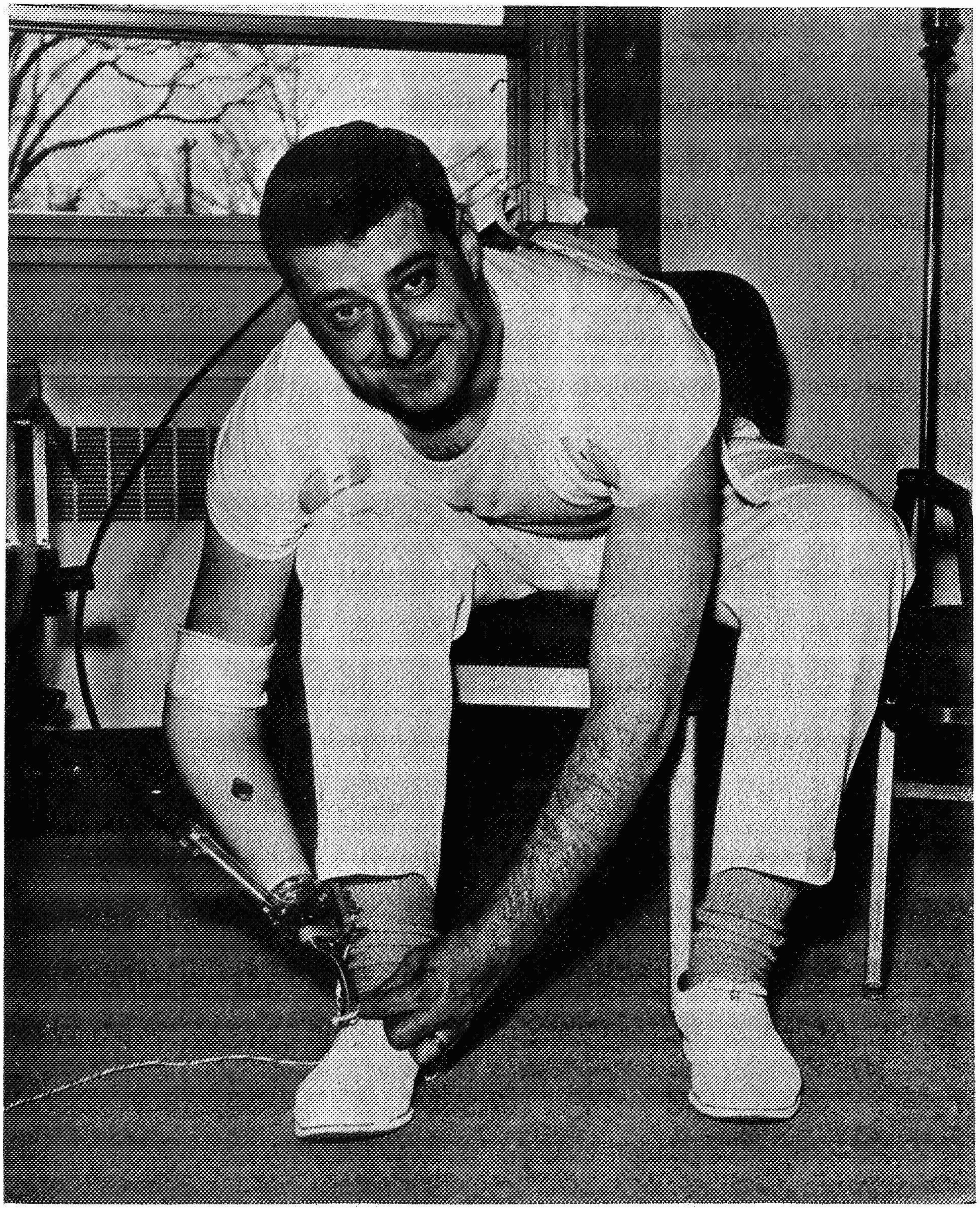

Fig. 21-14.– Demonstration of the use of upper extremity prosthesis.

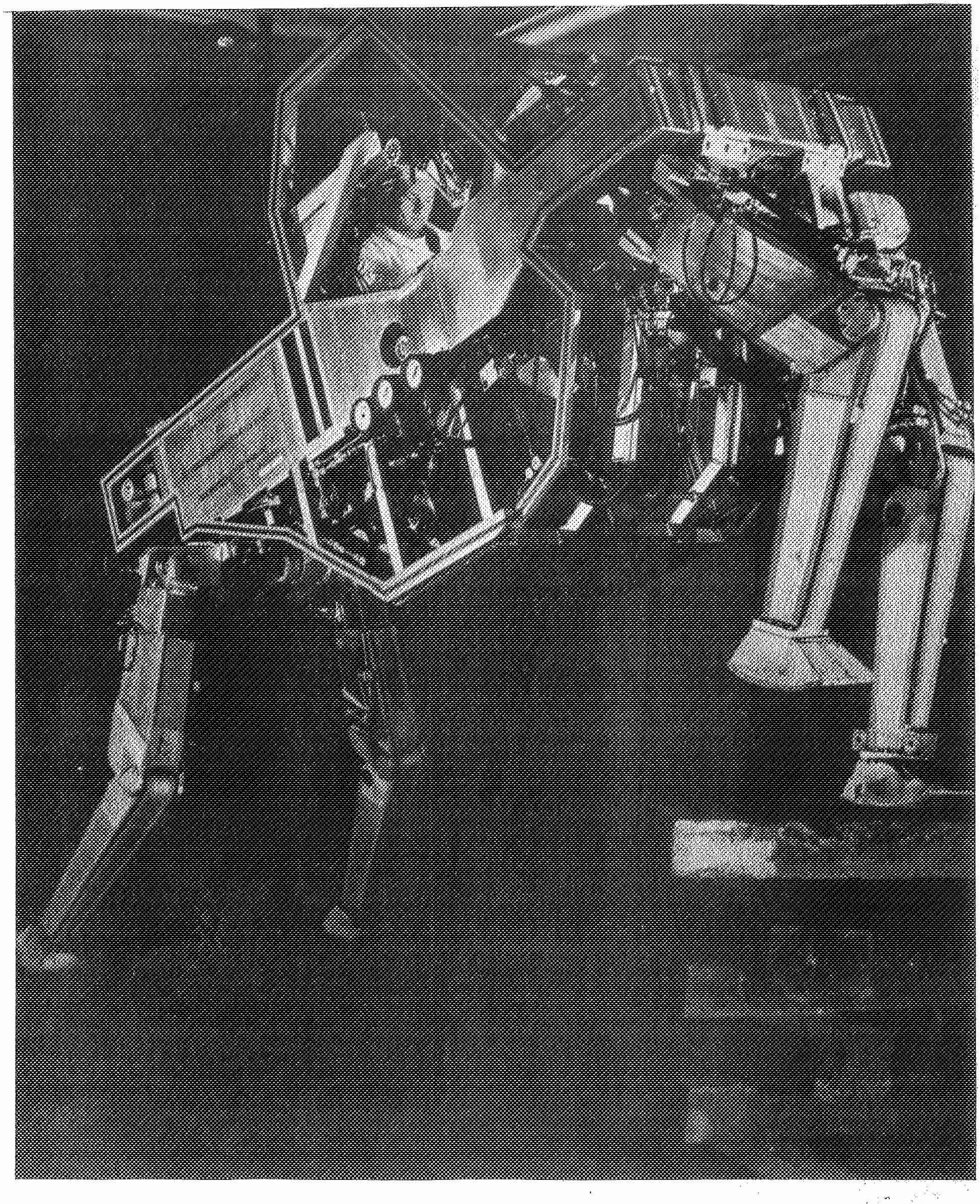

Fig. 21-15.– Control of CAMS quadruped vehicle.

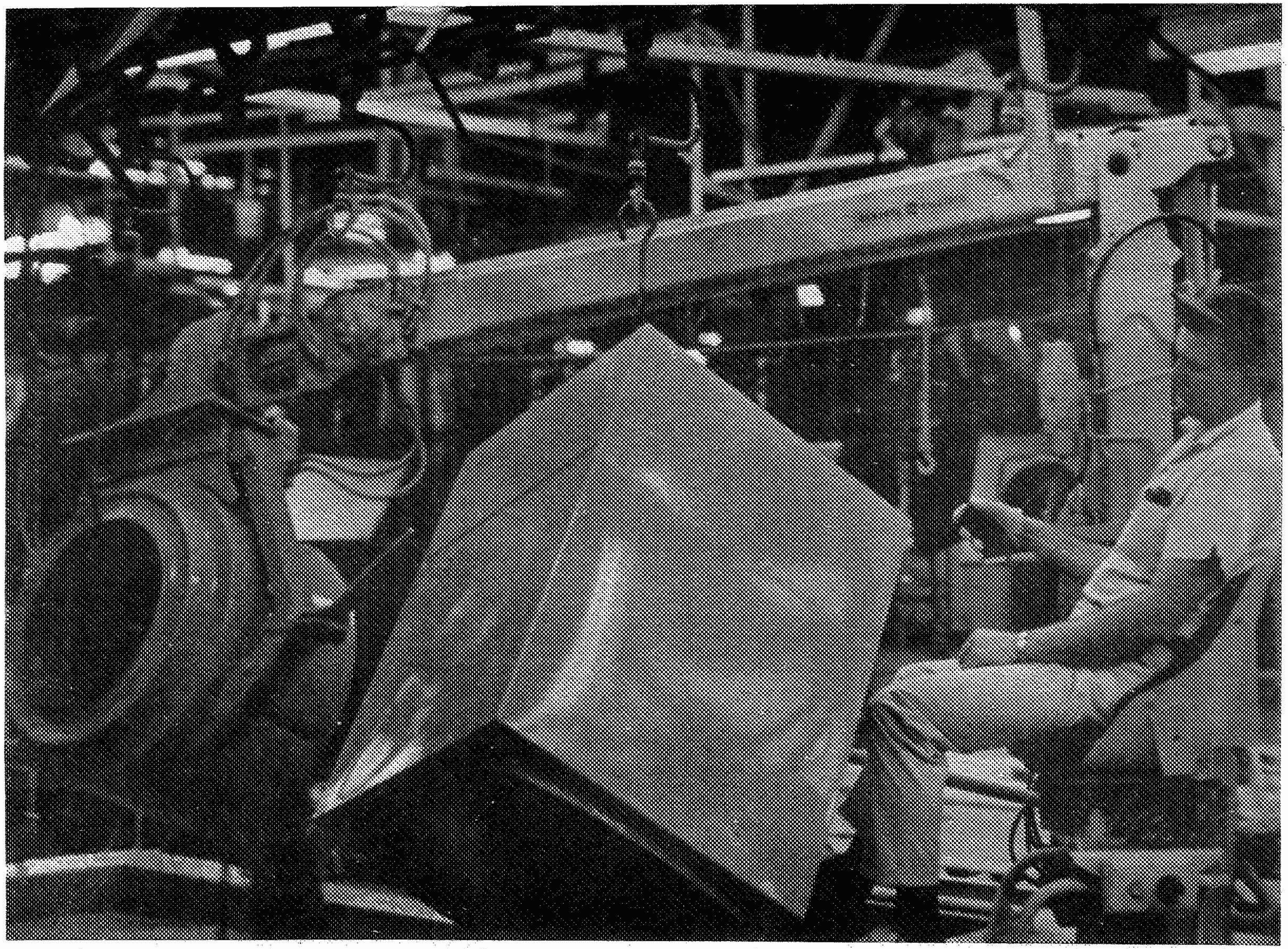

Fig. 21-16.– In-factory application of an industrial master-slave machine.

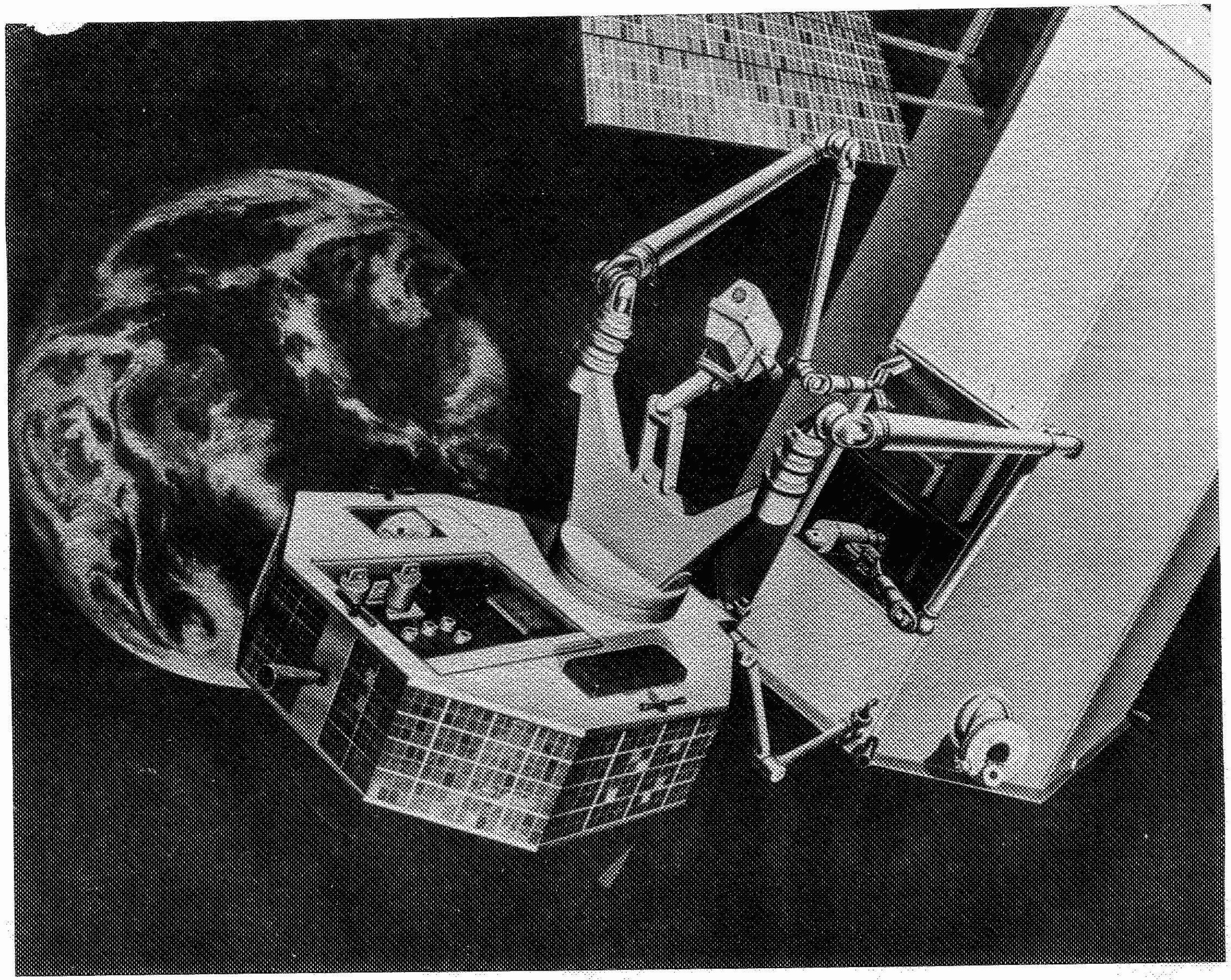

Fig. 21-17.– Radio-dispatched space maintenance system shown replacing an electronic module.

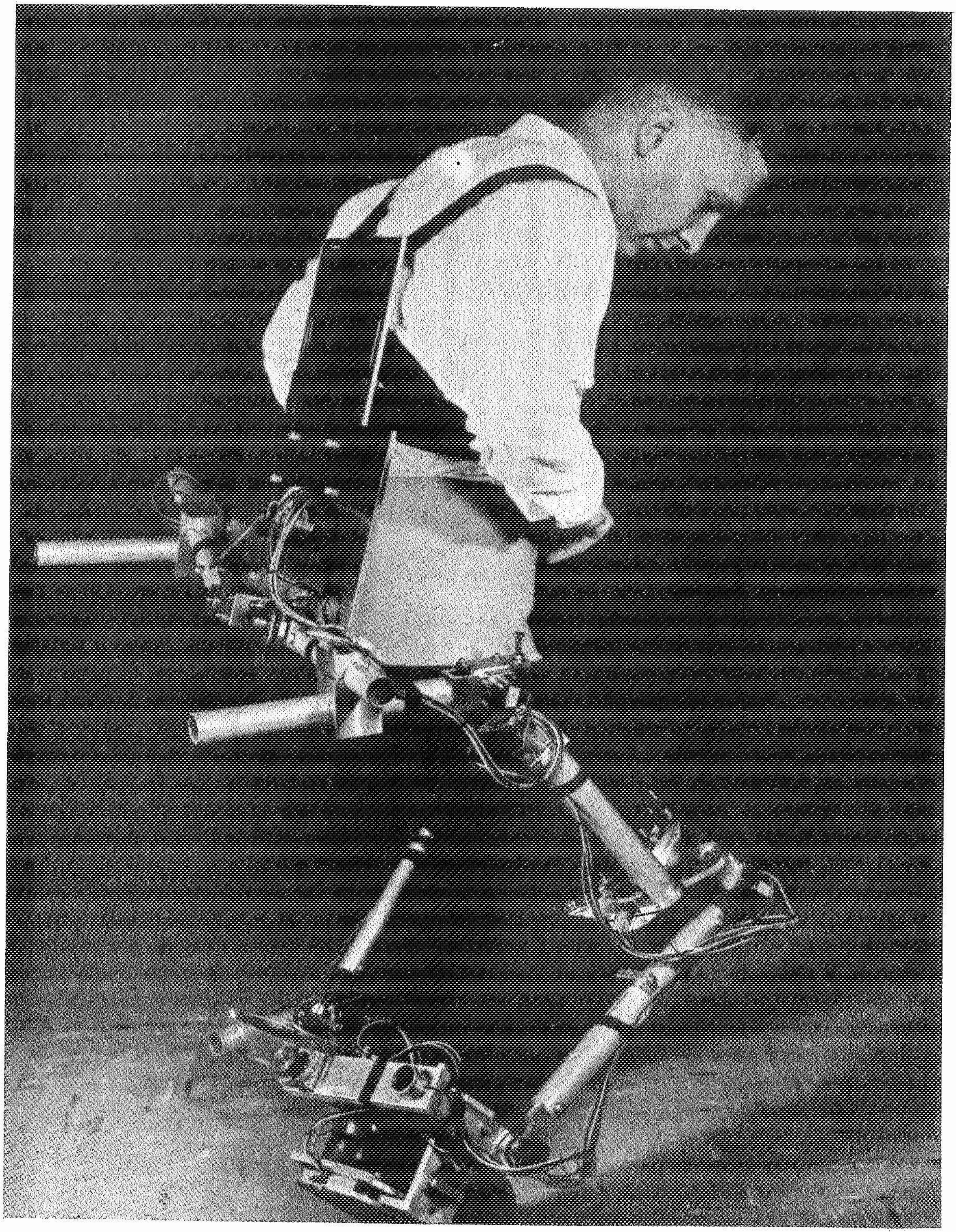

Fig. 21-18.– Laboratory manipulator simulation.

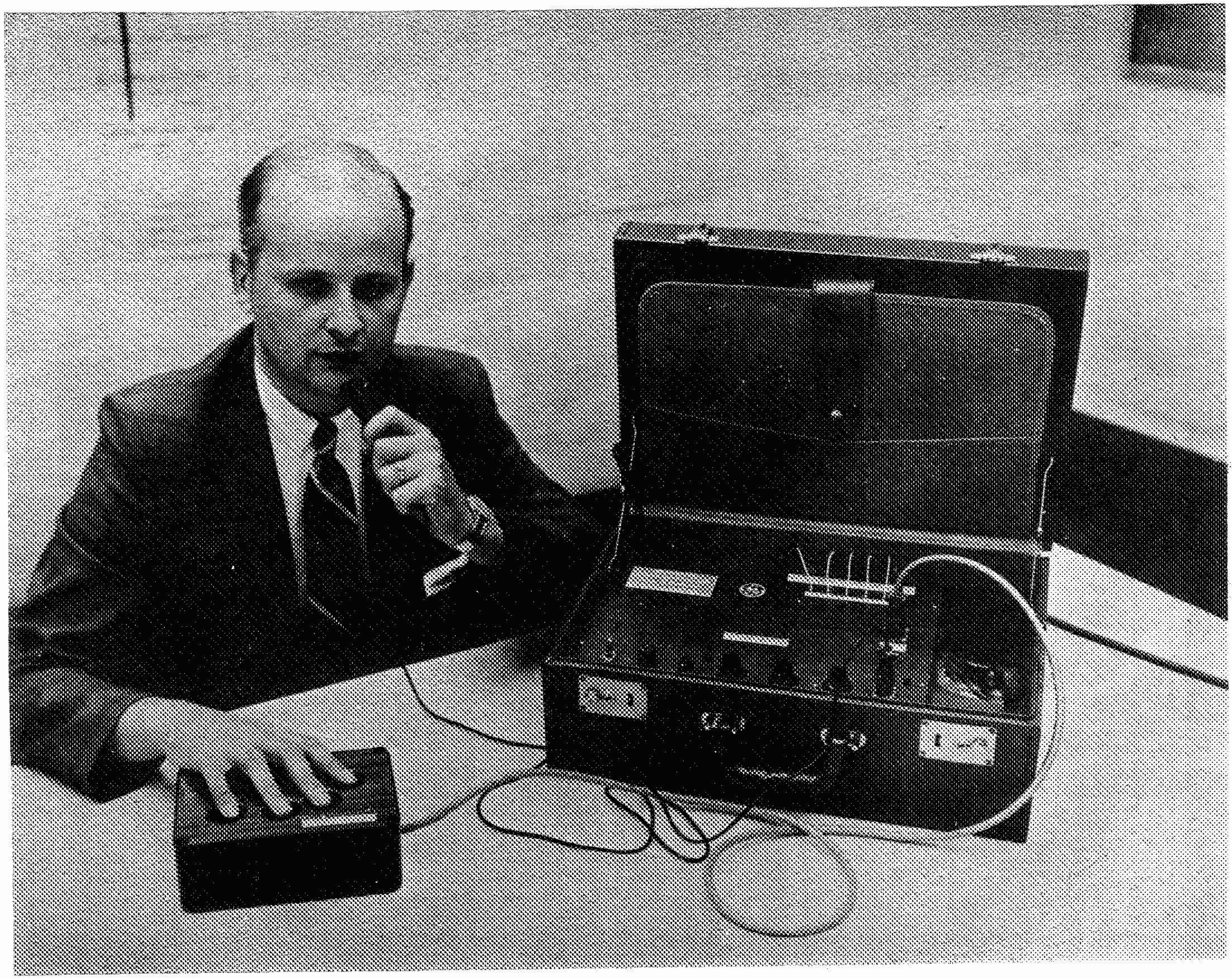

Fig. 21-19.– Blind-deaf communicator.

Chapter 22

THE ROLE OF INTELLIGENT MECHANICAL AIDS

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Stanford Research Institute

Reswick showed us a little glimpse into the past with a couple of early patents (Chap. 14). Here we take a look into the future—ahead of the current technology to something that we believe will pay off sometime down the road.

There is a kind of a common theme running through earlier discussions—the application of control theory, or at least the assumption that it is required for an understanding of the role of the human in the physical control of exoskeletal or prosthetic or engineering devices to assist him in some task.

The Artificial Intelligence Group at Stanford Research Institute is concerned with getting computers, or information-processing systems, to try to exhibit some of the aspects of what we call intelligent behavior. In particular, we have achieved notoriety in the press by having a demonstration vehicle, Shakey the Robot, which represents our venture into the subfield of this field of artificial intelligence—namely, robotry, in which the computer system is dealing with physical objects, or controlling mechanical systems that move around in a physical world.

Artificial intelligence is a rather young embryonic subsidiary of computer research, and is concerned largely with pattern recognition—looking at visual scenes or other sensory patterns, or scenes of information, and analyzing them to discover their content. Another concern is problem solving or theorem proving—how you get a computer system to make a plan, and using some formal planning language or mechanisms to carry out some desired task. A third area of interest is the use of language, or linguistic constructs more or less similar to human language, as a vehicle for representing knowledge about the world or about the system it is dealing with.

So we are working here in a field where a computer system somehow exercises cognitive control of a vehicle or system performing a task, rather than having direct human motor control that vehicle or system. Thus, the trend is toward less human control of the machine at the physical level, and closing the muscular servo loop through the machine level. We look toward the day when the user—patient, subject, or handicapped—might be able to express the task in linguistic or cognitive terms or to the computer, which simply "knows" what the task is—for example feeding a patient or assisting him out of a bed and into a wheelchair and so forth. In other words, the machine knows the task, at a cognitive level, and programs the mechanical device to accomplish it much more autonomously than is possible with current devices.

Such developments will not come all at once but in little steps, and certainly there will be a convergence of teleoperator or exoskeletal technology and the various devices discussed here with the more autonomous computer system. And mission orientation will dictate an integration of appropriate systems by various groups in the field, rather than each going its separate way.

Shakey the Robot is one of the steps along the route outlined. This robot has been developed at SRI; similar but independent work is underway at Stanford University, MIT (Chap. 23), the University of Edinburgh in Scotland, and several other centers around the world.

Figure 22-1 shows the device, which is about the size and shape of a small refrigerator, weighs about 200 lb, moves around on wheels, and is fitted with a television camera in its head assembly. It is connected by radio to a medium-sized time shared digital computer and receives instructions by means of a teletypewriter connected to the computer.

Shakey is a manipulator only in the crudest sense, because we never managed to get around to putting arms on the vehicle, so the only way Shakey has of affecting this world of his is to push things around. Incidentally, the little wires on the front, called "cat's whiskers," are push detectors. Thus, Shakey has three types of sensory input—TV camera, the visual range finder mounted up in its head assembly, and the cat's whisker sensors, which tell whether it is in contact with an object and pushing it.

The similar projects at Stanford University and MIT have manipulative hands. In fact, in some cases they may be prosthetic assemblies that have been modified and become computer hands. We often refer to them as *hand-eye projects*, because their emphasis has been on manipulations that can be performed with such a device and a TV camera eye.

At this stage of our work, it is not really conceptually critical whether we have a robot that moves around or we have hands that work with blocks and objects on a table, because we are still trying to study some of the fundamental information structuring and problem-solving processes. Different projects will vary in emphasis. We have to be concerned about the sort of dead-reckoning facilities of our robot as it moves around the room. It has to keep track of where it is. And it ultimately has to notice that if it keeps track by dead reckoning of its wheel motions, it will accumulate an error and not be where it thinks it is.

In the artificial intelligence community, there is a relatively new and important emphasis on the handling of language to represent tasks and to represent their solutions. We and other laboratories will be participating soon, we believe, in a speech understanding project. The goal is to create a computer system that can deal with natural human utterances in the domain of some task.

In the past, much work has gone on in word recognition. It has now been rather widely recognized that the recognition of isolated words is a different matter from the recognition of speech, as well as the handling of ambiguities in speech and the various malformations that we human speakers produce in our spoken outputs, must be treated as a research topic in itself and cannot simply be a direct extension of the older attempts in word recognition.

Another current development that may be even more significant to the area of aid to the neurologically handicapped is an awakened interest in scene perception. As noted in connection with the robot, we have done research work toward looking at a visual scene on a TV camera, analyzing the light intensity patterns, and trying to find objects. The goal now is to find directly the structure of the physical objects in a scene, using various types of depth finders, and we think the time is coming now when instead of getting a pictorial representation and then trying to analyze that to get back the objects in a scene, we will be able to find the locations and the presence and the configurations of objects directly.

We plan to tie this together with the work of manipulators, such as those now used in industry, to couple them to the world they are working in so that they can "see" what they are working with, be flexible in moving around and acquiring what they are working with, and act on it appropriately. This ultimately will have direct application to aids for the handicapped in providing an ability to sense the environment, sense the configuration, find out where something is and get it. Such applications are far different from shop practice where the thing you are dealing with is held in some sort of a jig or fixture and you simply know it is within a few millimeters of where it is supposed to be.

So we see new kinds of closing of the loop here—in essence, a closing of the control loop for this computer system on a more abstract level. The system will have some knowledge at a more cognitive or conceptual level of the task to be performed, uses vision, tactile senses as described by Bliss (Chap. 16) and others and whatever sensors are appropriate to learn about the immediate environment and to adapt its motions and organize its behavior to carry out a task at the level of a servo command or a preprogrammed command, such as assisting a handicapped subject from one conveyance to another.

We don't consider that this will become an achievement in the near future, but we are working on something that will in due course pay off and pay off very handsomely in allowing much more capable and much more useful machines in certain task domains.

We have given you a little glimpse into what we believe will be one component of the future here. We do not mean to argue for any inattention to the world of teleoperators; rather, we are suggesting that in the future, that world will be augmented by the capability for the computer system to take over the organization of the task of a mechanical aid, at a higher level and a more cognitive level and thus to have other means of assisting the humans that it is serving.

DISCUSSION*

Q. What sort of logic do you have in the machine for economy of operation? For instance, what you showed us with the cubes was not the easiest way to get the three blocks together. Is it done in some arbitrary sequential fashion?

A. There is some logic on the robot, but it is just bread and butter stuff—communications logic. The brain of the robot, as it were, resides in a computer on the other side of the room, which you didn't see. I think you were asking about that, really, the logic for pushing boxes together. Since we are studying the organization of a logical procedure, we really have a rather large and generalized computer program that is able to take the English command, make it into a formula in predicate calculus, and turn to a mathematical theorem prover for constructing the solution. The solution which then told the robot to get the three objects together by pushing object A to object B and then going over and pushing object C to object B.

Q. What is the principle of that very process? Why not go B, C, A, or why not push them all together? What is set forth?

A. Some of the axioms available to that problem solver don't tell it about, for example, the effect of having two boxes stacked up and pushing both of them, partly for the good reason that the state of our pushing art at that time wouldn't have permitted it. The robot can't work all by itself—we have to give it rules about what the world is—and the rules told it you can push something to somewhere else. But we didn't give it knowledge about pushing a stack of objects. It could conceivably be done.

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*The conference presentation included a narrated film, to which much of this discussion pertains. This 25-minute film, "Shakey: Experiments in Robot Planning and Learning," reviews some recent experiments performed with the Stanford Research Institute robot. The film begins by explaining the general features of Shakey and of his controlling programs. One feature of special interest is Shakey's ability to use the solutions to old problems as an aid in planning the solution to a new problem. Shakey also has the ability to recover from a variety of errors and accidents that may occur as he executes problem solutions in a laboratory environment. The film concludes with a demonstration of Shakey performing two tasks that exercise these various abilities. This color and sound film may be rented from SRI for a $20 rental fee (to cover costs of film reproduction and mailing). Interested persons should contact Dee Leitner, Room G037, Stanford Research Institute, Menlo Park, California 94025.

Q. But there is nothing that minimizes, there is no minimum path or minimum time or minimum effort?

A. Well, something has been minimized. I think it is a minimum complexity of solution in some conceptual sense. If you want three things together, you have the simplest operations available to you. If you were a pack rat and wanted to get three things together, you would probably just go get one and bring it to where another one is, or you might bring all three to a common place. The simplest solution depends on the simplicity of operators available to this robot.

Q. Is there any other way of having the computer know the position in the room? Does the computer continue to distinguish between the objects once they are pushed together?

A. The answer to the first question is that as a development of its program the robot can choose to take a television picture of, for example, the corner of the room or where it thinks roughly the corner of the room is, by looking for the visual boundary between the wall and the floor or for the baseboards in the room, or by taking a direct range reading of its position relative to the room. The program is arranged to do this when its accumulative estimate of positional error exceeds some allowance.

In answer to the second question, the robot considers the objects to be separate objects, at least in what we were doing currently. It will have said they are all nominally in the same place, although they are of course not obviously occupying the same circle of control. It has three objects all at the same named location, because that is the way we set up the information structure. If we wanted to think that it created a new object of the three, we could have put axioms into the system where it says if so and so is done, now you have super object. And it could have dealt with that conception.

Q. Coming back to the rehab connotation, one has to agree that man will inevitably go in this direction toward more sophistication. I also think one has to bear in mind very firmly the way in which biological mechanisms function. We know a great deal about our environment, and what we do as a result is appropriately generated and effected by motor efferent signals and there's maybe a really important penalty to pay if one withdraws too much of the "naturality," as it were, of the outgoing signals in a rehabilitating situation. The actual process of generating outgoing signals, which then establish an efferent copy in the central nervous system so it knows what has been done, is part of the learning process and may be one of the most important aspects of rehabilitation in some concepts. Would you agree?

A. Well, yes. I wouldn't dare disagree! I have noted that we are in no sense working on a substitute for other things, other techniques that must be built into a robot to enable it to cope with the world. It is as if we are looking toward the design of a higher level of the robot, but we do not ignore the fact that the robot's own kinesthetics and loop closings must all be there also. If you were referring to the role of a robot or other mechanical aid in human rehabilitation, I am not sure I have anything to offer.

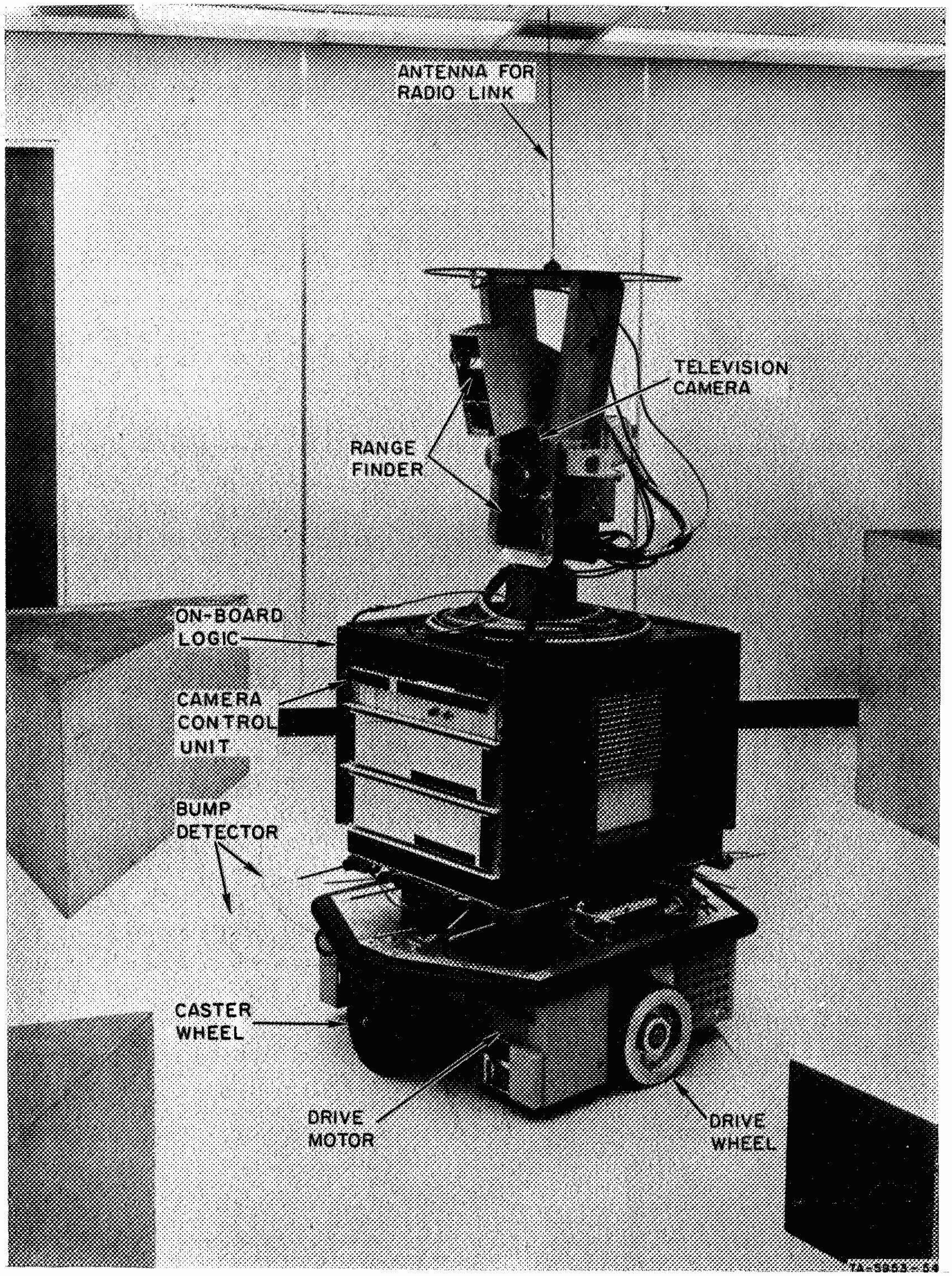

Fig. 22-1.– Shakey the robot.

Chapter 23

SUPERVISORY CONTROL SYSTEMS

Thomas B. Sheridan
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Supervisory control lies between computer control on the one hand and neuromuscular continuous feedback control on the other.

For example, let's draw a little man without any limbs, as shown in Figure 23-1. Let's assume his cognitive capabilities are relatively intact; he has sensors, but somehow he is "caged" in the sense that his limbs are hanging outside. He does not really have as continuous and natural control of them as he would like, relative to the environment and to environmental objects he would like to move about and with respect to which he would like to move himself.

We make no claims for having worked in a rehabilitation area, but I would like to think that some of what we have been doing for NASA might apply. Sometimes it is best to compromise between computer control of a purely artificial intelligence sort, where you say to the robot, "Please do such and such, good-bye, good luck," on the one hand, and a tight loop closure on the other, where each and every action continuously requires feedback in this closed loop.

We got into this kind of research about eight years ago when we became interested in the problem of time delays in control loops of the sort that are encountered by controlling devices on the moon or in space where there is a radio transmission delay due to the speed of light. William Ferrell in our lab used a fairly simple manipulator device that was master-slave, but had a variable loop delay in it—a pure delay, not a physical inertial lag. Ferrell showed (Fig. 23-2) that one can predict how long it takes to complete a task quite easily as a function of the tolerance in positioning required by the task, which he called an "index of difficulty," and as a function of the time delay. Completion time is shown as the ordinate scaled logarithmically with levels of delay as a variable. On the abscissa is the index of difficulty. The task was very simple—to move the manipulator, grab a block, move it a certain distance, locate it within a certain tolerance, release it, and draw back. He went on to experiment with some other kinds of tasks. He was able to fit the experimental data very nicely by some simple-minded models. The time it took to complete the test was very predictable.

We later went on to do the same kind of task with 7 complete degrees of freedom manipulators. The same kind of result occurred. Manipulation with such a device with no delay takes about ten times as long as it takes with bare hands.

The delay problem in and of itself is not so important in rehabilitation, but it is an example of what might be called a barrier or a caging process. We decided that for reasons of difficulty in using teleoperators with delay, and for other reasons that separated the operator from a natural relationship with his end effector, it would be good to use some computer control. We started using the term *supervisory control,* which has come to mean a kind of control that is partway between pure computer control or artificial intelligence on the one hand and continuous control on the other (Fig. 23-3).

In the middle is some barrier, which could be a time delay, a noisy connection, or an intermittent connection. The human operator needs some way of talking to the system on the other end and some kind of display of what results. This doesn't look very much like a prosthesis or a rehabilitation situation, but try to think of it if you would in terms of that. Somewhere there is an end effector that does interact with the outside world, and there probably need to be some artificial sensors. We assume for our purposes that visual sensors convey a picture back to the man. If we are talking about blind persons who also have neuromuscular difficulties, then of course we are in real trouble. Probably some kind of tactile sensors are available plus other kinds of exteroceptors in conjunction with the arm devices.

In Figure 23-3, there are two blocks designating two rather different computer functions. The right hand one (remote) is analogous to the peripheral nervous system itself, where once a command is given consciously, an action is carried out at the far end without conscious control. The computer at the left (local) is meant to be a kind of modeling or testing experiment operation, which is utilized prior to actually committing an action. So for driving a teleoperator in space, one first would give commands to a local model, to work through what one wanted to do and make sure the coding and language was all right. Then one would commit a signal for the teleoperator to act across the barrier. This action would be carried out by the computerized peripheral nervous system.

One can think, for example, of a continuum from the robot on the one hand—again, our terminology is that of space application—to an astronaut in EVA on the other hand, as in Figure 23-4. There is something in between—teleoperation—which if we are talking about pure master-slave manipulation would be closer to the astronaut in EVA. If we are talking about supervisory control, it would be closer to the autonomous robot, which is pure artificial intelligence, if you will.

About five years ago, we decided to implement a system of this kind. We strapped together a mechanical arm, (nuclear hot lab type) to a computer connected into two different kinds of input devices. One kind of input device was a teletype and another kind of input was a multidegree of freedom joy stick. We demonstrated that one could give commands to a mechanical arm through a small computer by instructing it to go do such and such, which means move certain degrees of freedom, until certain conditions are met. One condition is that interoceptors—resolvers or potentiometers in the various joints of the mechanical arm—indicate that you reached a certain place. A second is that exteroceptors—meaning here the relatively crude touch sensors on the hand—bumped into something.

There were three kinds of conclusions from this experience. First, there were implications for what you might call the language of how a person talks to a computer. The predicate calculus notion, which Munson discusses in Chapter 22, is part of this. But a tougher problem is the interface between the man and the console, or the means by which he actually makes his will known to the device. There are people working on natural language inputs. Practicality is a little far down the pike yet. The artificial intelligence group here at Stanford has made some impressive demonstrations of talking to a computer. But for our kinds of applications and rehabilitation, we are probably talking about some far simpler codings. In our own experiments, we used a teletype for the person to instruct the beast. We called that kind of communication *symbolic*.

Symbolic commands we distinguished from analogic, where we use our hands to point, or to move steering wheels, or joy sticks. Clearly, what one would like is some combination of symbolic controls and analogic controls—a simple switch, perhaps, if it is on in the direction you want to go and off in the direction you don't want to go. However, symbolic codes, the kind of muscle movements involved in speaking, don't necessarily correspond to the direction in which somebody is being told to go, in an analogic or geometric way. This is an area in which a lot more research is needed.

A second implication of our experiments was that somehow a computer that is being told to do something has got to have an internal model of what the task is. Munson also refers to the internal model notion. Several of our students, in particular Dan Whitney and Phil Hardin, in their two doctoral theses, did some research to this point.

Figure 23-5 shows about 12 different kinds of functions a computer serves in connecting the man, with his displays and controls, to an external environment, the manipulator activators and the interoceptors that are in the actuators, and to the interosensors and the motors or the actuators to drive the sensors. Incidentally, these are two rather different functions. We have muscles in our eyes and we also have sensors in our arms.

If a computer is going to deal formally with problems of interacting with the external environment, it has to have a way of thinking about these kinds of tasks. One means is through what control engineers have come to call *state space representation*. A very simple example is shown in Figure 23-6. If we want to move ahead in one dimension, grab an object and move it back in one dimension, we can represent the various manipulations involved by a three-dimensional state space. One dimension is for closing the jaws on the object, another has to do with moving the jaws, and the third has to do with the position of the object. So a trajectory in that three-dimensional state space becomes a specific and unique way of performing the task. If one can specify various no-noes in the state space, like the fact that you can't run your hand through a solid metal wall and you can't move the object unless you are grasping it, one can apply optimum control techniques—and there are very many ways that one can search spaces or linear graphs to be "optimum"—to determine a best way of performing the task. As the task gets more and more complex and gets more degrees of freedom with more objects or more limb motions, a very, very complicated computer indeed is required simply to represent all of the different possibilities. The state space goes up geometrically as the number of dimensions of the task. So, beyond very simple tasks, this technique won't work.

A second kind of study looked at ways one could interpose a new computational element between the state space optimization technique (where the manipulator is driven by the state space) and the human supervisor. Its job would be to sort out the subtasks.

You all know the little puzzle where there are 16 little blocks and there is one open space and you have to move different blocks in different directions to get blocks to line up so they are in order, one, two, three, four. Well, Hardin worked with this kind of a problem, which is not unlike the problem of sorting out objects in the real world, or the problem of a moving crew that must move a piano from way back in the storage room in spite of all kinds of furniture stacked in front of it. Let's say each of the moving men knows how to pick up an object and carry it in a straight line and dump it, or even avoid objects, but he doesn't quite have the ability to sort out which object to move first, which to move second, and which to store locally until you can do something else and put the first object back, and so on. So Hardin's programs, which are implemented on the big Artificial Intelligence computer at MIT, perform this kind of function, which Hardin called a "task tree" (Fig. 23-7). This function is simply a way of stacking up trees of subtasks, such that all these tasks have to get done before you can say you are finished. In some cases, you want to move objects out of the way and do other things and then put objects back. Hardin's whole way of looking at this problem was in terms of a task tree, or an "end" tree.

It looks as though advanced rehabilitative systems are going to have structures something like that in Figure 23-8, with manipulation hardware, a man, and executive routines that listen to requests or listen to statements about subtasks from a human operator, sort them out, and give them over to some semioptimization routine, which finally drives the manipulator or mobility device.

One of the implications of our earlier study is this linguistic aspect, and another is the task model. A third aspect has to do with the directional resolution of the arm. When one moves his arm and wants to go in a certain direction, he doesn't think very consciously about the fact that certain muscles move a certain degree and in certain proportions at certain stages of the process in order to achieve the desired result. If you have a mechanical arm with a certain kinesthetic configuration, there are some matrix equations that you can solve, such that you can say to the arm, "Go in the direction the finger is pointing, or go in this direction or go in some combination of those directions," and without worrying about all of the joints, the arm will carry out that motion. Dr. Whitney in our group actually did implement this kind of system. He did it first on a modified Rancho arm and now is working with a more sophisticated setup, which is a cooperative project at the MIT Draper Lab. A relatively more sophisticated computer interface is being built in conjunction with this project.

Returning to the primary concern here, rehabilitation engineering, it seems that when you get into supervisory control or computer control, where a man is stating a subgoal to a computer, you deal with not necessarily huge subgoals like "sweep the floor," but lesser subgoals like "go get the broom," "move in that direction until something happens," and so on. There clearly is an advantage in getting the job done, but there can be some disadvantages. One of these is the psychological problem of "productive orientation," as Erich Fromm put it–the degree of participation of the man in the act. Some would call it the joy of work, of doing something. In rehabilitation, human participation in the act is fairly important, and something to grab hold of one's arms and just force them through certain actions would hardly be a very satisfying way to live out one's life, though it might be more efficient. This is one kind of possible disadvantage to supervisory-computer control of prosthetic and orthotic devices, and it needs further thought and study.

The second kind of possible disadvantage is that some effects of the supervisory-computer control system, though programmed and requested by the human operator, might nevertheless result in nonintentional results.*

We appear to have reached the point in this business where some exciting possibilities can be imagined. Some of us have been dreaming about a really good exoskeleton–not the man-amplifier type of thing but something that is cosmetically relatively tightly fitting and provides a person multiple degrees-of-freedom, not just one or two, which a prosthetic arm might. Vykukal's design (Chap. 15) looks like it might be the first really good exoskeleton.

We don't have a really good interface between the computer and the exoskeleton. This is not a simple task; you can't just run the wires from the computer to the electric motors. General Electric has worked at this, and the Draper Lab at MIT at the moment is working hard to develop such an interface. But it is another piece of electronic hardware with functions that cannot be accomplished satisfactorily by an ordinary computer.

We also need a really good interface between the artificial interoceptors–the sensors in the mechanical arm itself–and the computer. Potentiometers have been used in the past. Optical decoders are indicated now in terms of low-cost and good wear. Good progress has been made toward a really good interface between the artificial exteroceptors–which see and feel and touch the outside world–and the computer. Bliss's discussion (Chap. 16) certainly corroborates this progress on the tactile side. Television is fairly highly developed, especially scanning by the image orthicon.

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*Norbert Weiner's last book before he died was called *God and Golum, Inc.* Golum, in the Hebraic tradition, is a half-formed man, which in Weiner's book was the computer. Weiner relates a tale of the "monkey's paw," which is a kind of a horror story of what can happen, if an act is programmed or requested and is carried out just the way you asked for it, but is accompanied by some other things that you didn't really anticipate.

In the fifth area, we are still in a bit of trouble—that is, in the interface between the man and the computer. Reswick's earlier developments with the "Case Arm" involved instructions given to a programmed arm to do certain feeding operations through some very clever instruments mounted on a hat. There have also been tongue switches. If we are going to try to have CP patients tell their will to a computer, and have that will carried out in pieces, we need a lot more thinking about this problem than we have had.

The idea of putting a person inside of an improved exoskeleton with computer control, some supervisory control, and eventually, perhaps giving a quadriplegic the ability to walk and run sounds a bit dreamy—but the components seem to be falling in place.

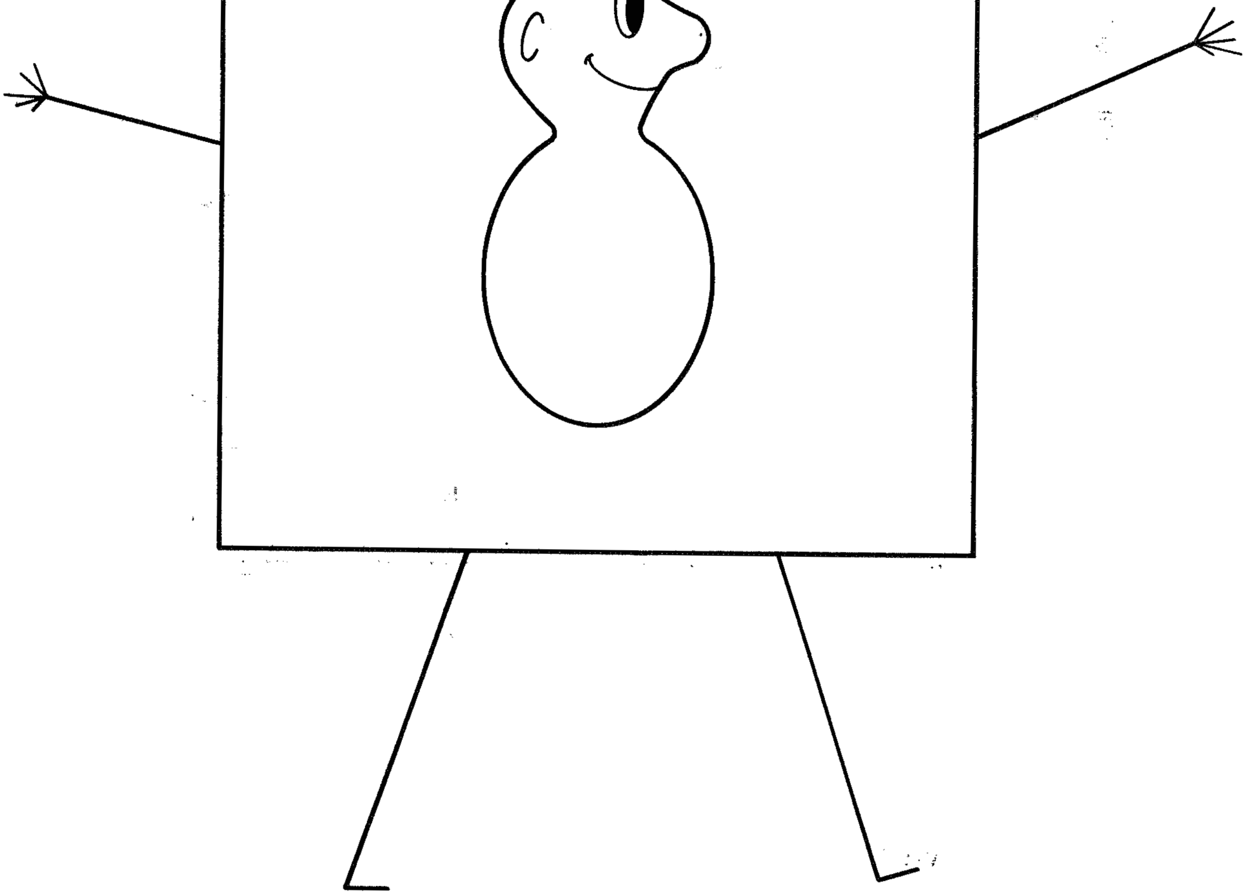
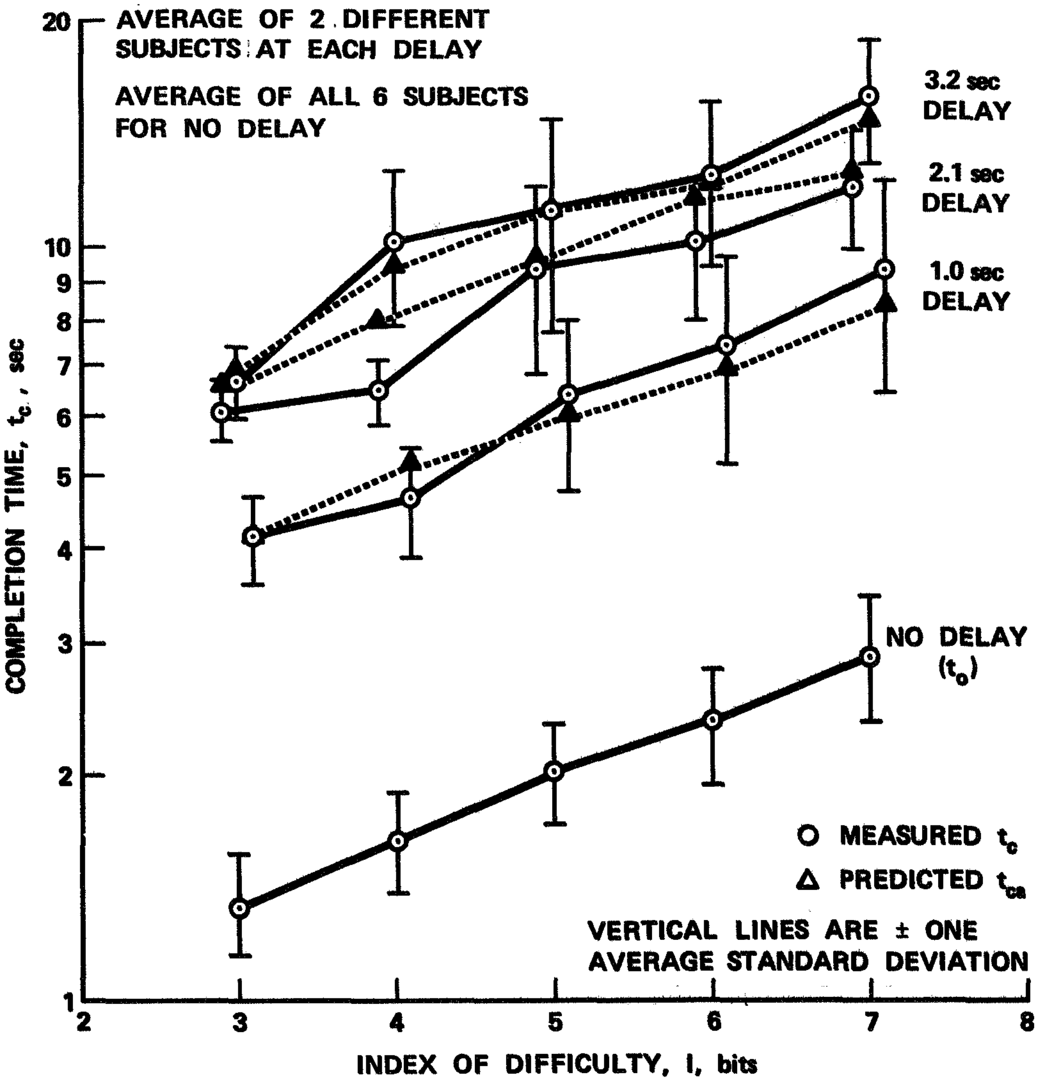


Fig. 23-1.– The "caged human being" problem – when mind and hands are necessarily separated, how to put them in better coordination.



$$t_{ca} = \frac{t_{c1} + t_{c2}}{2}$$

WHERE $t_{c1} = t_o + N(t_d + t_r) + t_d$

$t_{c2} = t_N + (N + 1)t_d$

t_o = AVERAGE COMPLETION TIME WITH NO DELAY

N = NUMBER OF TIMES OPERATOR MUST OPEN HIS EYES AND SAMPLE BETWEEN OPEN LOOP (BLIND) MOVES

t_d = LOOP DELAY PERIOD

t_r = REACTION TIME TO BEGIN MOVE

t_N = AVERAGE TIME REQUIRED TO PERFORM TASK IN OPEN LOOP CONDITION (VISUAL SAMPLES BETWEEN MOVES) WITH NO DELAY

Fig. 23-2.— Ferrell's results.

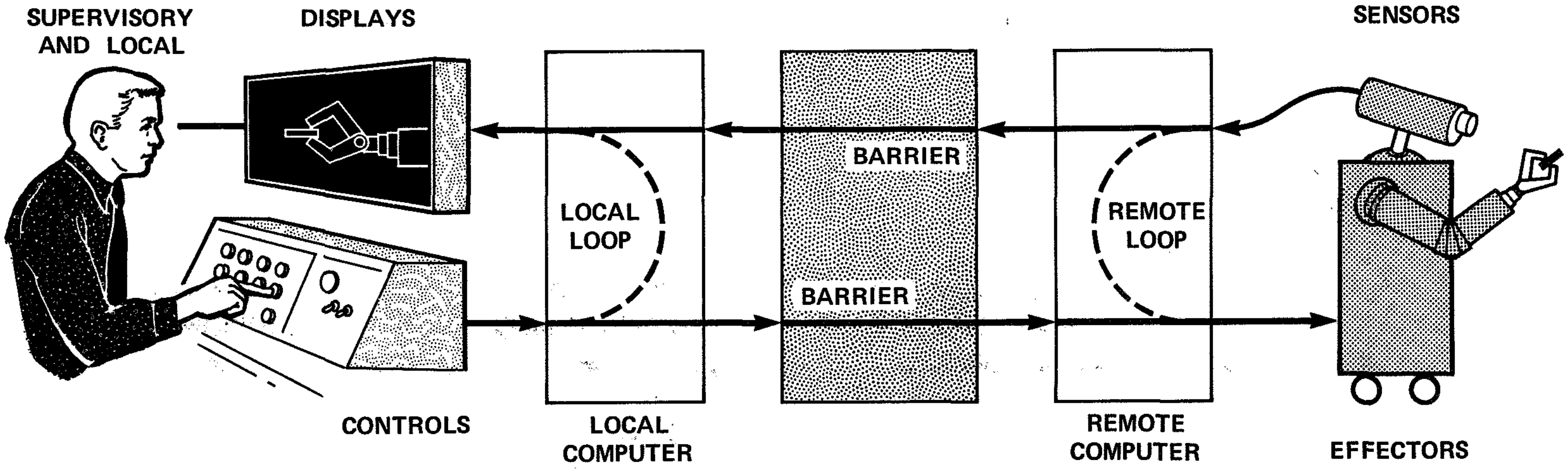


Fig. 23-3.– Schematic diagram of supervisory control of remote manipulation.

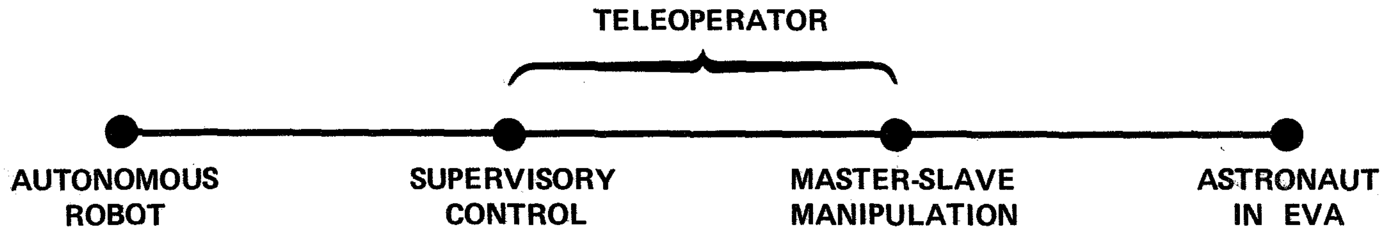
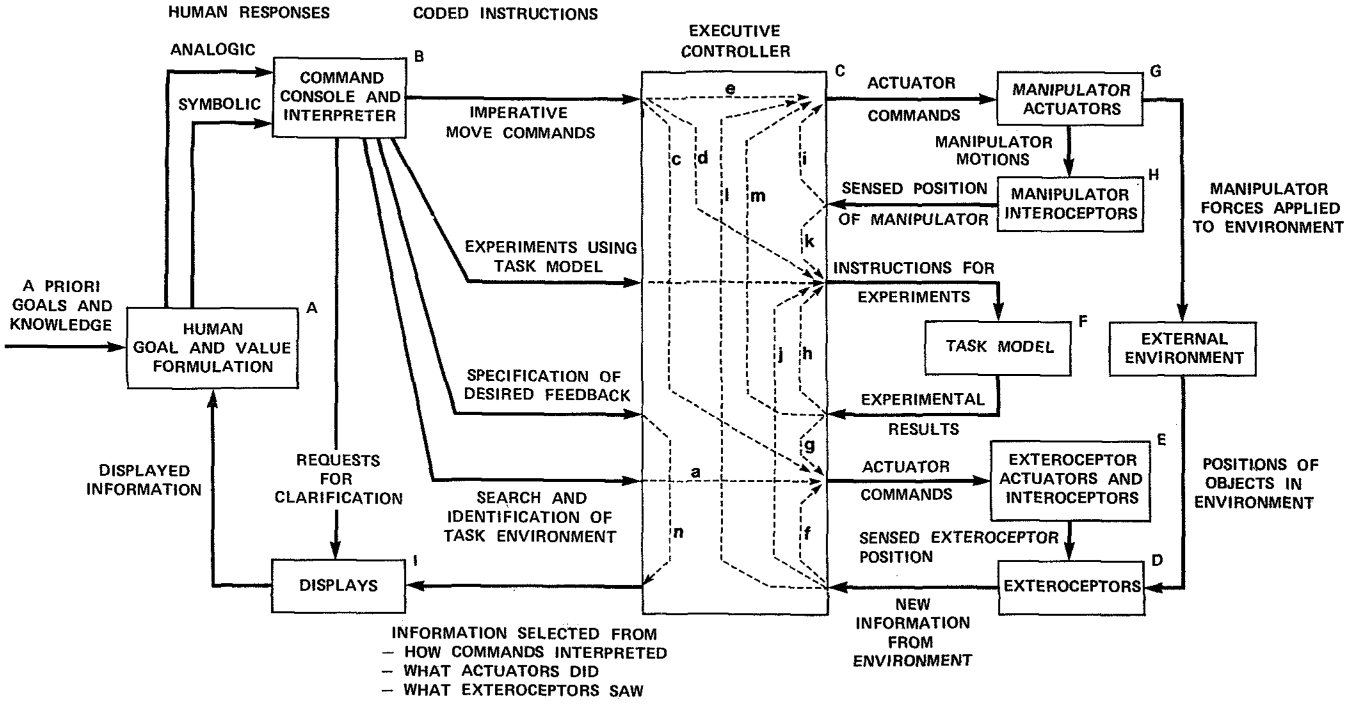


Fig. 23-4.– Continuum from completely automatic to completely manual control.



a. DIRECT INSTRUCTIONS TO EXTEROCEPTOR ACTUATORS

b. DIRECT INSTRUCTIONS TO PERFORM EXPERIMENTS ON TASK MODEL

c. INSTRUCTIONS TO EXTEROCEPTOR ACTUATORS AS PART OF MOVE STRATEGY

d. INSTRUCTIONS TO PERFORM TASK MODEL EXPERIMENTS AS PART OF MOVE STRATEGY

e. DIRECT INSTRUCTIONS TO MANIPULATOR ACTUATORS

f. MODIFICATION OF EXTEROCEPTOR POSITIONS AS A FUNCTION OF WHAT EXTEROCEPTORS SENSED

g. MODIFICATION OF EXTEROCEPTOR POSITIONS AS A FUNCTION OF TASK MODEL EXPERIMENTS

h. EXECUTION OF TASK MODEL EXPERIMENTS AS A FUNCTION OF PREVIOUS EXPERIMENT RESULTS

i. MANIPULATOR POSITION FEEDBACK CONTROL

j. UPDATING OF TASK MODEL AS A FUNCTION OF NEW INFORMATION ON THE ENVIRONMENT

k. UPDATING OF TASK MODEL AS A FUNCTION OF WHERE MANIPULATOR IS

l. MANIPULATOR CONTROL AS A FUNCTION OF NEW INFORMATION ON THE ENVIRONMENT

m. MANIPULATOR CONTROL AS A FUNCTION OF TASK MODEL EXPERIMENT RESULTS

n. INFORMATION SELECTION FOR DISPLAY

Fig. 23-5.– Functional taxonomy of supervisory control of computer/manipulator.

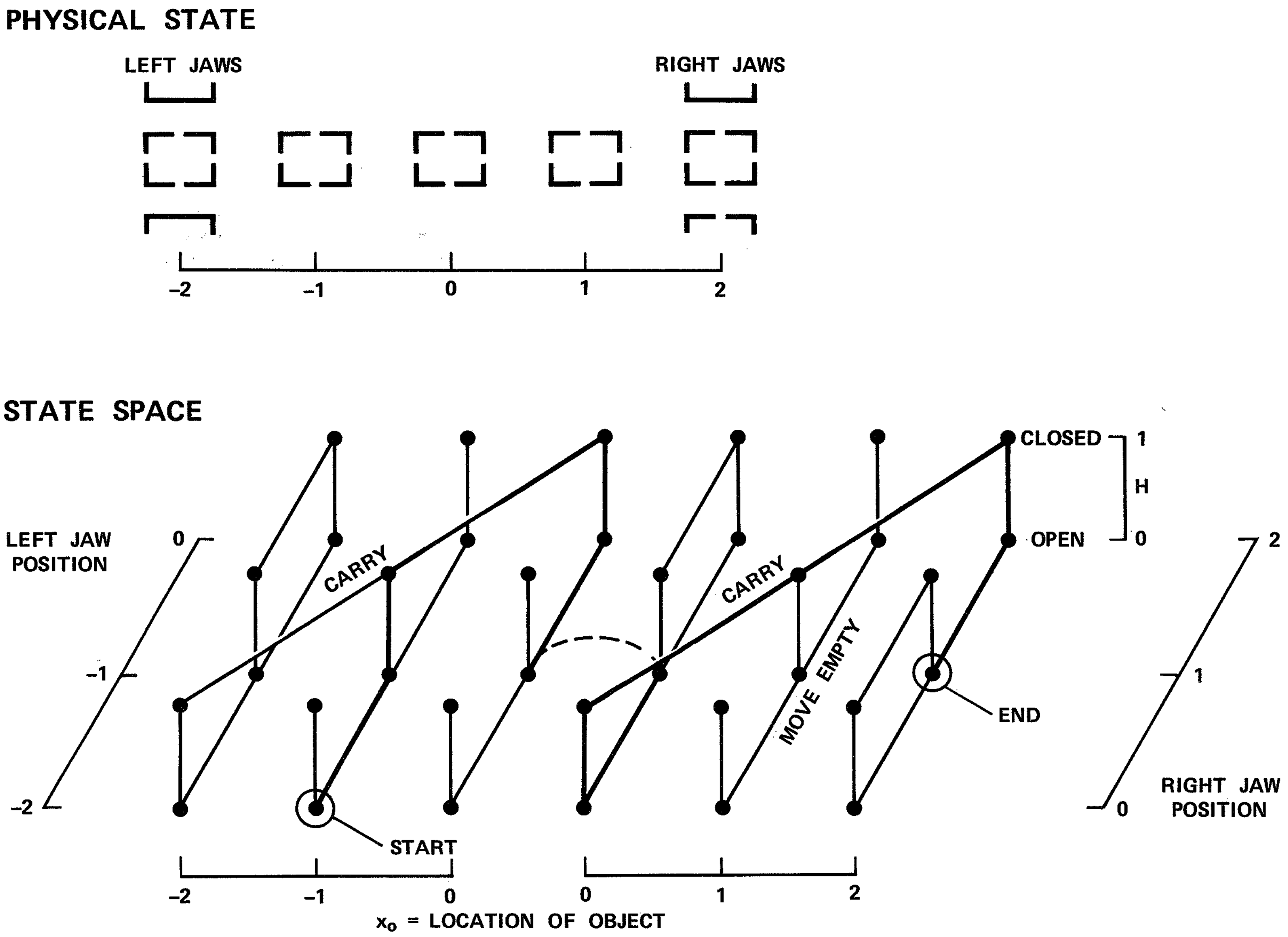


Fig. 23-6.– Example of Whitney state space for simple one-dimensional physical task.

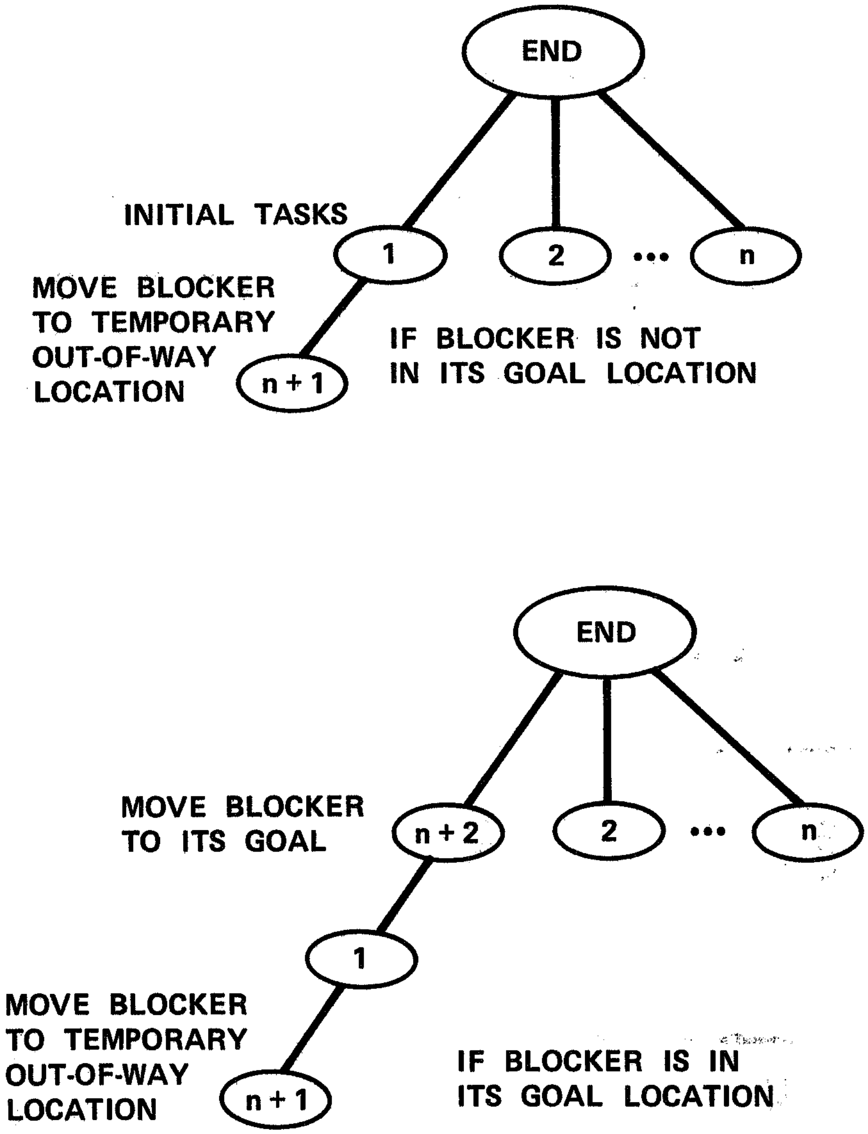


Fig. 23-7.– Schematics of Hardin "Task Tree" executive routines for manipulation subtask planning.

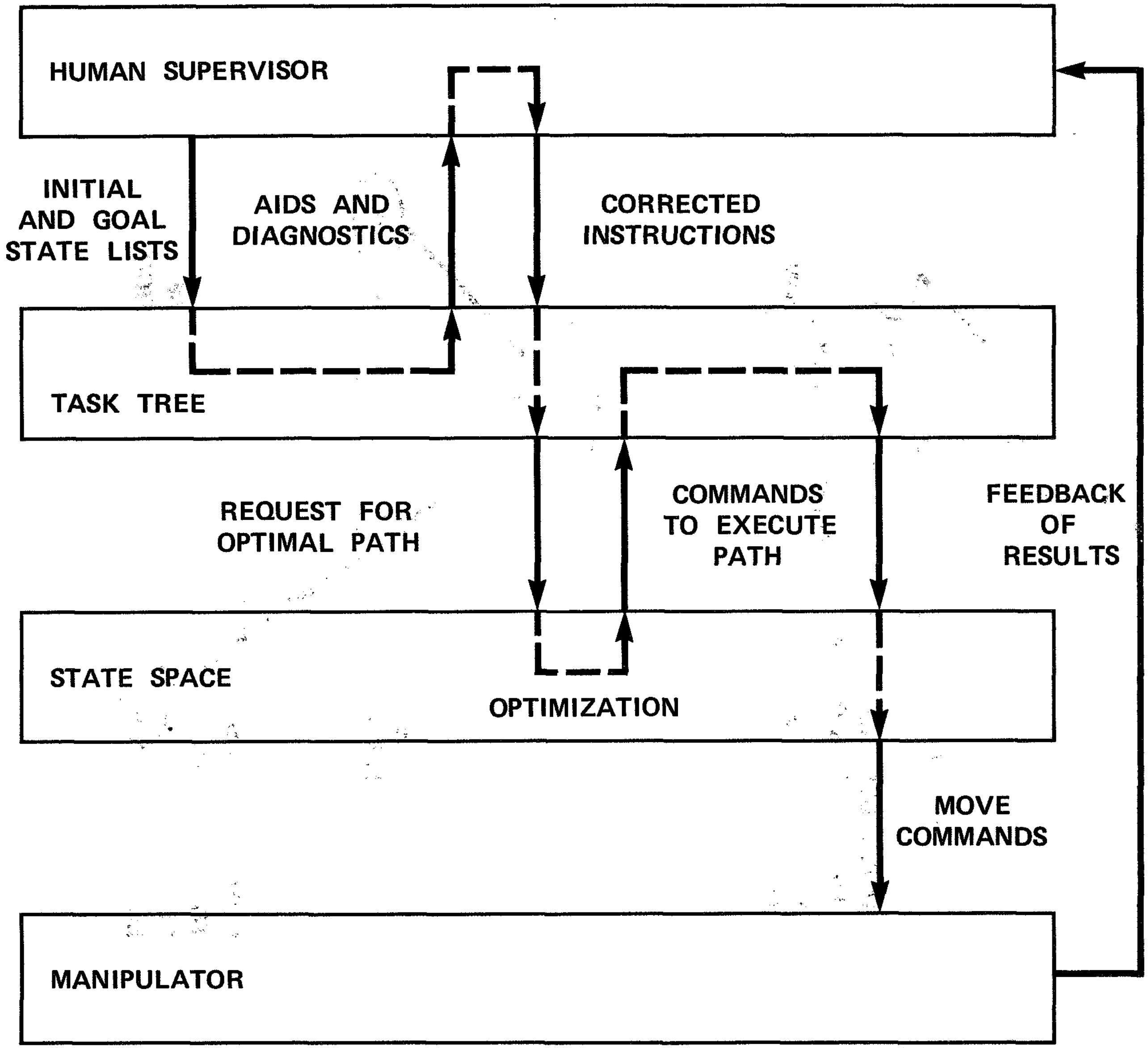


Fig. 23-8.– Hierarchy of control levels in Hardin's supervisory control system.

GENERAL DISCUSSION

Dr. Lee Arnold, Chairman

The Conference on Technology and the Neurologically Handicapped closed with a discussion of communication among the disciplines and of the major problem areas. The discussion was led by specialists in specific areas. These included clinical medicine (Dr. Berenberg), neurophysiology (Dr. Melvill Jones), engineering (Dr. Reswick), and rehabilitation (Dr. McLaurin).

Arnold: President Nixon has stated that: "We must create jobs to ensure the maximum enlistment of America's technology in meeting the challenges of peace . . . [there is a] need for new programs to encourage the use of America's enormous wealth of scientific and technological talent for social purposes." In bringing the collective expertise of so many in technological fields, medicine, and government to bear on the problems of the neurologically handicapped, this conference is a particularly timely and relevant demonstration of the President's words.

Before we begin the final session of our technical program, Mrs. Goldenson [representing the United Cerebral Palsy Foundation] would like to make a few remarks.

Mrs. Goldenson: I am a complete amateur, and I am very much honored to be here with all the experts. As one of the pioneers of United Cerebral Palsy, I just wanted to thank Dr. Billingham and Dr. Lee Arnold for arranging for this Conference. I am excited by what I think are the possibilities that could result from the Conference, and I want to thank everyone for the hard work which has gone into their contributions. It is one of the thrills of my life to have been here.

Arnold: Thank you, Mrs. Goldenson. As has been pointed out, there have been efforts all through the years to create interdisciplinary activities. A few years back, when I was a consultant to NASA Headquarters, I tried to bring about a joint effort between NASA and New York City. A meeting was held involving the top New York administrators, deputy mayors and others at their level, plus a NASA contingent headed by Tom Payne, who was then the Deputy Administrator. It was the wrong topic, and the desire for cooperation in the city was not universal.

We don't have that problem here. Many of us have felt for years that a natural interdisciplinary activity would be one involving engineering and applied science on the one hand, and the medical profession on the other. I would like to call on Drs. Berenberg, Reswick, McLaurin, and Melvill Jones to begin a further discussion. I hope we can get many view-points on how to more efficiently create an effective interdisciplinary effort of this kind. We will start with Dr. Berenberg, who is Professor of Medicine at Harvard, and who has been very much involved with cerebral palsy problems for many years.

Berenberg: I think no single organization at the moment is more appreciative of or excited about the prospects for the future than United Cerebral Palsy, but obviously there are all manner of handicapped individuals with all manner of neuromotor dysfunctions who will be equally appreciative in the future.

I believe that the name of the game, in a single word, is communication – communication among disciplines. When we get down to communicating, we use terms in utterly different ways. Someone says something I hear, but it doesn't make any sense at all because I am thinking of something unrelated. All you have to do is go down to South America and you realize that everybody outside the United States refers to everybody inside the United States as a Yankee. Inside the United States, the Southerners refer to the Northerners as Yankees. And the Northerners refer to the New Englanders as Yankees. New Englanders refer to somebody who lives in Vermont as a Yankee. And if you go to Vermont, a Yankee is somebody who has apple pie for breakfast. Vocabulary is a great problem that we are going to have to overcome if indeed we are going to succeed in communicating.

I think I sense an exciting commitment to purposes that are useful, a concept that I share. I can't speak for the engineering sciences, but in medicine we do have a problem, because we have many basic scientists who believe in science for science's sake and are firmly committed to the philosophy that if you do good research work it is going to be useful someday. That is all that matters. I think everybody in this room hopes someday is tomorrow, and that goal-oriented research does have its place. In no area is this more apparent than in NASA.

I would urge again that people give serious consideration to the matter of preventing neurological disabilities. Dr. McLaurin and I have been trying to collectively decide what the costs are. We have heard at this conference about the cost of bringing children to a school. In Massachusetts, the care of a handicapped child for his lifetime costs the state over a quarter of a million dollars. And if you add what the family puts in, the costs are astronomic.

We must place more emphasis on preventive medicine. For example, the possibilities for prevention of head injuries are really significant. The possibilities of improving monitoring facilities in utero are equally significant: one of my obstetrical colleagues who has spent a year and a half on one monitoring problem solved it with a single telephone call to MIT. It is this type of communication that is a prime need.

The whole matter of the threat to ecology and its effect on medicine is another area I think we will have to address in the future. As one example, a woman in Houston received $175,000 because she had been exposed to lead in significant amounts during her pregnancies, and had three retarded children "as a result." I don't know that it was as a result, but I do know that in Boston, the blood lead level of babies at the time of birth averages between 20 and 30, probably not a threatening amount. But we have had women with blood leads as high as 340. Work at the Einstein Medical Center has demonstrated very clearly that small amounts of lead, if given to a chicken, will produce a disastrous amount of malformation in the central nervous system.

To toss out another topic for comment, I know the wheelchair was a tremendously exciting thing. The exoskeletal concept is fascinating, and we talked about slaves. But the thing that bothers me about the exoskeleton is that the arm that is in that exoskeleton is not a slave to what you are going to have that exoskeleton do, unless it is a paralyzed arm. If you have an athetoid arm in the exoskeleton, the arm is a slave to something in the basal ganglia. It is a slave to the brain. And if you have an exoskeletal glove around a hand, the motor cortex is still going to be trying to exert control. Another master is involved, and in everything you do motorwise, you are the slave to what the brain tells you to do. If you put another master on top of it, the energy expenditure is frightful. I can remember when people treated distorted, moving athetoids while holding them in total braces in a position that amounted to crucifixion. These individuals, if you remember, couldn't tolerate it for long. The energy expenditure of being tied down when your brain is saying, "You must do this," is overwhelming. So you have a system in between, and the master in between, and it is not a total slave unless it is a paralytic one. When you are talking about a spinal cord paraplegic, then you are dealing with the central nervous system – a different system.

Of course we have covered a tremendous amount but all of us realize we just scratched the surface. Dr. Weiss and I were talking yesterday about the fact that we could have all this discussion about sensory problems but have not tackled the problem of hearing. You know, hearing aids are for those who have a conductive hearing loss. They should be improved, technologically. But the whole group of people in this country who have sensory neural hearing loss is huge. They are frequently people who have eye or muscular problems as well as hearing problems, which leads me to try to get somebody else involved in this. Dr. Weiss, where are we to go?

Weiss: It is a big order. I had an interesting experience recently. I was talking to a patient of mine who has a hereditary degenerative inner ear disease. His father had it, and he is worried about his children. He is going deaf, and is frightened by the prospect. For this reason, he decided to apply his good mind to the problem, and wanted some guidance as to what had been done. So I gave him some of the literature, and he came back to me aghast – "why is it that there are all these things we need doing but nobody is doing them?" I think that one of our problems is in the direction of energies, and this usually means money and people. There is a basic uniformity in scientific endeavor, and nature uses the same bricks in building everything. It just builds in slightly different ways. Someone working in the biochemistry of, say, the gastrointestinal system could apply his findings to the biochemistry of nerve cells. It is just a question of whether he does or not. It is partly a matter of training programs, and it is partly a matter of money. The fact is that medical schools bias the training of students in particular directions, and as you notice at Harvard, the present core curriculum has reduced the specialty training programs that are mandatory to a minimum, and they become electives. In the long run, we are going to have a more difficult time getting people directed into subspecialty areas because they will have become committed to the more general areas sooner. I think the reason we have so many scientists and engineers these days is that the government, after the Second World War, was willing to pump large sums of money into the training of scientists. I remember that there was some talk of putting money also into medical school training, but this was prevented by the politics of the situation. And we now have a seeming shortage of physicians, although there is some dispute as to whether we are short of physicians or not. I think that this is the kind of long-term priority that has to be set up. We are not going to solve these problems tomorrow, as much as we would like to.

Berenberg: Wait a minute. We can solve some of them on a short-term basis. You know, it is probably only a few miles from Harvard Avenue to MIT.

Weiss: I think that is the crucial point. As it is now, the value of a conference like this is it lets people know about the work of other people who are attacking the same problem from a different viewpoint.

Berenberg: My students today are taking electives at MIT and that is a great step forward.

From the audience: Following up on your comment on sensory aid developments, I would like to talk about two areas in which I think NASA technology may be especially applicable. One is in some improved proprioception for patients who lack this capability. The Boston Arm shows the beginning of some excellent technology in this area, and I think a lot more can be done, particularly in helping with gait problems. Aside from proprioception, balance is a problem for most patients; perhaps some sort of sensory aid could help such people walk. Not much has been done in these areas, and I think there are practical possibilities. It is an area that we should look at from the point of view of applying new technology.

Berenberg: The problem of balance again is not nearly as simple as purely vestibular control.

From the audience: I am not saying that the problems are easy.

Berenberg: I think we have not tackled disorders of the basal ganglia and the cerebellum and a lot of other areas that are perhaps more complex in terms of their technology.

From the audience: I think what you said is very germane, but I think it should be expressed a little bit differently, or generalized in a different way. Any attack on these problems requires a team effort. It has been my experience that if you turn the engineer loose, you will come up with what the engineer thinks should be done, but this usually does not coincide with what the doctor thinks should be done. Unless there is a team effort, I think to a certain extent that it is not the bioengineer but the physician who is the prime mover. He has to be the prime mover and enlist the aid of the engineer.

From the audience: Engineers with new ideas like those I have seen at NASA can only apply their concepts if they can take leave for a while and work with a team, a medical team. They have to become deeply involved in the problems to make a really significant advance.

Mann: I hope we are beginning to mature beyond the point where we rely upon fortuitous, accidental, and serendipitous combinations of people. In my remarks (Chapter 13) I deliberately pointed out that the existing scheme of things is analogous to falling and breaking a hip and then just happening to get into a clinical situation with a Mel Glimcher, who is not only an excellent orthopedic surgeon but is also broadly concerned with other aspects of the biological system. In an environment like MIT one can operate in an entrepreneurial sort of way, and beg, steal, and borrow computer time and other kinds of facilities, and begin to do things, and then others become involved through chance contacts. We shouldn't rely on this kind of an accidental acquisition of resources. We have to assemble teams of people who tackle these problems in a more systematic fashion. I hope we are growing up to the point where we will do it in a more deliberate way.

Arnold: The purpose of this conference was to bring the agencies together, to find out what is happening and what their thinking is; to get the disciplines together and find out what their thinking is; to show that there is mutual interest, and to promote constructive interaction. This, in a sense, was a planning conference as well, and there are very important things we have to do from this point on. And as you remarked, the mission concept might be a very important way of doing this. At this meeting we have had just a very limited sample of the sorts of things that can be done. But we have to make a very efficient survey and a very efficient matching of the right sorts of people to get on with this problem.

McLaurin: Early in the meeting, somebody made the remark about coupling engineering technology with medical services. I think we should maybe take a close look at who needs to be coupled with whom. If we look at the technological side, we can see a whole lot of information that we have gathered through the years. We have many, many technical people with great competence and resources. They are working in universities and special centers like Ames. They may be working in industry. All this kind of talent could be very effectively spearheaded to accomplish some specific mission through the efforts of NASA.

On the other side, we have a much more complicated picture – we have patients, millions of them, with many kinds of disorders, and every one an individual. Each one of these individuals is surrounded by his own cell, which may be his family or friends. He is helped in rehabilitation services by several groups. It may be a school, a general hospital, or a rehabilitation center. In each one, there are various specialists who can do certain things for him. But they vary. Some rehabilitation centers are very primitive: there isn't much there besides a doctor and a few therapists and nurses. Others are much more elaborate; they have several types of therapy – occupational, physical, speech, and so on – they have schools for people, and they have engineering capability in the shape of several engineers who can understand almost anything that goes on. These are exceptions. The various groups and institutions serving the patient are supported by several different agencies – an insurance company, state government, federal government, or private endowment. All these individuals and groups and interests have to be brought together if we are going to have an effective team. There are instances in certain specific areas, like perhaps technical aids, where attempts are made to bring all these problems together and give some kind of overall cooperative guidance. I think we all agree that a great deal can be gained by getting medicine and engineering together. Unfortunately, there seems to be one great big "white-out" between the two. And I don't want to interpret this as being some kind of snow job. It is just that somebody over there in engineering could be very starry-eyed about the thought of several thousand or a million severely disabled people becoming active and real good citizens. Somebody over here in medicine, perhaps a poor therapist who has trouble finding $100 a year to buy plastic to make hand splints, can be baffled by a complex powered exoskeleton. And throughout this big white-out, every once in a while, some sort of glamorous solutions pop out.

One example of how technology can become a human aid is a gadget used by a golfer to improve his stroke. He stands up, something holds his head to keep his eyes on the ball, something holds his waist, so that he can get the proper swing, and something holds his hands, and so on. The whole thing is very cleverly put together. The only thing that remains is to put this thing on the golf course so that he can take it out on the fairways. Now, I don't know what his particular handicap is. We can all imagine what it would be like to carry in public some sort of gadget like this.

In addressing the problem of how to get some really good, close working cooperation between engineering and medicine, we must not underestimate the difficulties. First, we must think of how the people in medicine can define problems in a way that the engineers can understand. We must get them together to talk about it and perhaps come up with some solutions that might work, then go back and see if they can apply some prototypes in two or three cases, then examine the results, and so on. I don't think there is any chance of our really drawing some communication lines here in this conference, but if we could address ourselves to this whole idea of coupling a tremendous national resource to a vast complex human problem, perhaps we can come up with some kind of a start, some kind of a suggestion as to what is the next logical step in getting together, so that when we do come together we can have a rather happy result. I would be very interested in hearing from the engineers working in NASA just what kind of contact they want.

From the audience: There is an important difference, having to do with mission orientation as discussed earlier, between the well-defined engineering goal of getting to the Moon and the medical world's great big mishmash of a great many different problems. The only medical analogy to reaching the Moon is the prevention or cure of a single disease. But even here, the "solution" of a disease problem has many components – the natural history of the disease, the etiology, the pathophysiology, the diagnosis, treatment, and prevention, the ultimate goal being prevention and the next best thing a sure cure. As you work out all the various subquestions of the disease problem, (and the better the intellectual effort at that stage), the easier it is to identify areas in which meaningful interaction can be had with the engineering people. There also is an enormous difference in the size of these problems. The engineers face great big things; whereas these medical problems comprise innumerable smaller ones.

McLaurin: You are suggesting some more intelligent homework by the doctors?

From the audience: Right.

Wyatt: It seems to me that perhaps getting the problems from the medical community side into the milieu of a NASA team isn't really what ought to be done here. We talk about the transfers of technology. I think that one of the things that we ought to be looking for is the transfer of the techniques, not the assignment of task to a group having a demonstrated capacity in a certain area. You allude to the fact that you have a multifaceted and very complex problem in medicine, and you infer that you have relatively straightforward problems on the technological side. NASA is the outgrowth of an organization known as NACA, the National Advisory Committee for Aeronautics, which was chartered 56 years ago. Its charter was very simple: it was to study the problems of flight with a view to their practical solution. We have been working for 56 years. We have not solved all the problems of flight. They are very complex. But we have made progress by focusing team efforts on certain aspects of those problems as they could be identified and as they could be sorted out in terms of priorities. I think this is the answer, and it goes back to what Dr. Mann referred to. You have to identify your problem. It is not a question of basic or applied research, but a question of focused research and development. I think the big challenge is how to focus on identifying the problems that ought to be solved and what kind of teams are to be organized, including what kind of organizations ought to be involved. And I would suggest to you that you don't give a job like this to NASA. NASA is a mission-oriented agency. We have contributions to make. But you do have to get together teams whose purpose in life is the solution of the problems that you are trying to tackle. I think this is one thing we ought to keep foremost in our minds. There are technical contributions that we can undoubtedly make, but the big prime need here is how to organize to tackle a problem in a way that is going to be fruitful. In a word, identify the problem, focus on it, and put your teams together.

From the audience: These medical teams have to be motivated teams that grow to encompass a knowledge of engineering technology. I don't think the concept of taking the two sides and sort of Scotch-taping them together is right. You have to have the team get it all together in one head or one set of heads.

From the audience: I want to answer what Mr. Hambrecht said earlier and what you are saying here. You can't solve a problem just by having engineers. The engineer must get into the patient area so that he knows what a patient is like, and what some of the problems are. It occurs to me now that it might not be at all a bad idea to get some of the therapists and physicians into the advanced technology area where they can see promising techniques to pick up that might not be thought of by the engineer. I feel very strongly that the engineer and others involved must see and work with the patients they are trying to serve.

From the audience: I am in the engineering field and have worked with people on both sides of the fence. And I have found that you effectively have to perform an infiltration, so to speak, before you can achieve communication. Say we wanted to find a mission, one of the tasks a nurse would have to perform and a doctor would have to perform, and the tools that would have to be applied. What is the timing factor, what are the various aspects involved in interrelationships among the medical people and the patient, and what is the overall goal? If necessary, we should even lay this out on a functional block diagram, take a look at every piece, and lay it out so that it actually looks like the piece of a puzzle. You can follow this all the way through. And all of a sudden you have people developing insights. The doctor says, "Uh-huh, this is my part." And the engineer says, "Well, this is how I can help you do various things." You can now look at it graphically, so to speak. Now both sides will begin to contribute.

From the audience: There are two things, it seems to me, that we are merging here. One is to look at NASA as a supermarket. Somebody goes in as a purchasing agent and looks around, and he says "these devices are great for my problem." He takes them and tries to use them. The other thing is getting somebody with bioengineering knowledge or engineering knowledge and have them involved in the solution of the problem and in devising new engineering techniques to focus on the problem rather than just picking a lot of things off the shelf and trying to use them. I think they are two rather different concepts: (1) getting in and solving the problem means that the engineer is full time on the research team solving the disease problems, as opposed to (2) being primarily involved in NASA and conversing lightly with those who have the major responsibility for the problems.

Hsu: Is there some provision at NASA or any of the other agencies for young physicians or people interested in this problem to spend a certain period of time working in this area? Then a physician could understand what technology is available and how things could be brought together closer. As an example, I am the product of a U. S. Public Health program that was set up at Johns Hopkins to train people in the specialties. At the conclusion of the training program, participants went into the basic sciences, so that they would be able to understand fundamental processes and then bring this knowledge to bear on the clinical situation. A similar arrangement in NASA would be very helpful.

From the audience: I don't think that the team concept is a real problem, because everyone in the room has demonstrated an interest in seeing it achieved. The question is, how do you get the focus, and how do you get the coupling? It seems to me one of the questions worth considering is whether you want a grand design or a group of small designs in these mission-oriented activities.

Mann: It just isn't good enough to have a guy at NASA from time to time, or somebody at MIT, make that phone call to work it out. In formulating the mission and the groups that will address themselves to the mission, we have to recognize it is going to cost money. And these programs are going to have to be handled over a sustained period of time. Look around at the people who are currently involved in doing interesting, hopefully significant things in the area of physical and sensory rehabilitation, and you will find that in almost all cases, in one way or another, they are entrepreneurial types. They operate out of bases like universities or the medical profession or some other kind of a construct that gives them great freedom to do whatever they want to do. They are not salaried by some organization specifically to do a certain sort of thing. That is great for them, and it is great for the work they can do from their own vantage point. But if you really want to get on with the job, you have to recognize the fact that it is going to take funding over a sustained period of time to build up the kinds of groups and develop the kinds of programs needed to produce the end results we are seeking.

From the audience: I think Dr. Mann has made a terribly important point, that of having clear missions. I think there is a great problem in defining missions honestly and in the effort to make the problem big enough to attract the funding necessary to put together the team. It is easy to exaggerate, perhaps, the universality of a mission. I am worried, for example, about lumping hemiplegics together as a group, giving a statistic – there are 2 million hemiplegics – and saying we need a certain kind of prosthesis to help them, when in fact the group is very inhomogeneous. I think the statistics that the medical people throw out may persuade the engineer to think this problem is much more discrete and much larger in terms of numbers of patients than in fact it is. One can funnel great amounts of energy and money into something that turns out to have applicability to a fraction of one percent of the group that the engineer thought he was setting out to help.

McLaurin: Very true, unless the engineer actually lives with the problem.

From the audience: I think unless he insists on asking some very tough questions of the people that he is working under.

From the audience: The NASA paradigm, if you like, has been a very revealing one, as a great mission-oriented concept. But we have to keep clearly in mind that it has been a rather unique event in American history and that one shouldn't fall into the trap of thinking, well, maybe there will be something like the NASA mission that will come along for medicine or come along for something else. I submit that NASA is unique, and we will just have to look at less well-defined problems as we try to generate the support for medical research.

From the audience: The Subcommittee on Engineering and Clinical Care of the National Academy of Engineering is developing a proposal that includes the three features that many of the last speakers have named. The proposal says that NASA type technology is required, but it takes the people there to transfer this technology; that these people must be paid and employed full time on the health care problems; and that they must be working in the hospital environment. The National Academy of Engineering proposal basically is asking for funding for significant numbers of people to be transferred to hospital environments. The problems addressed by the Academy differ somewhat from those of interest here, but the concept is valid – funding the work of people with the appropriate interests and abilities on a semipermanent basis in the medical environment.

From the audience: The analogy given earlier of the cure of a disease to a landing on the moon appears to have limited applicability because in the rehabilitation field, we are dealing in general with the residue of trauma or disease, or we are dealing with human beings who are partly whole and partly affected. The distinction between impairment and disability is important, for the physical loss and the functional loss need not be parallel. And this means, of course, that the patients are not passive ingredients in this problem but active ones. They are not "programmed," and of course they are heterogeneous, not only because their physical impairment varies, but because of their ability to adapt to this impairment. The human side, which I think is scientifically analyzable, shouldn't be thrown out in a scientific group merely because we haven't analyzed it yet. In other words, I think this is not just acceptance, which is very often the simple approach to it; it is the ability of the individual to bring his own human adaptive mechanisms into some sort of accommodation with technological devices. This is another dimension of the engineering side of the problem.

McLaurin: And as you do things for the patient, then his needs change and you keep updating more and more.

Mrs. Goldenson: What we are talking about condenses itself very easily to the essential problem and to the human being. The big scientific agencies concerned with medical problems did not exist 15 years ago, but the problems have always been with us, and, in fact, to a large extent led to the formation of these agencies. I know that is true of the Neurological Institute, because my husband was one of those people who worked all year to help establish an agency of the government that would be concerned with cerebral palsy.

From the audience: How could we interest industry in the contributions and role of aerospace research? There are some very important problems here. Most of the things we need are not of such universal use that very many need to be produced. The big industries can't produce except in large quantities. So it is extremely difficult to adapt industries to this kind of work, although they may contribute some knowledge and know-how in a manner similar to NASA. This problem has to be overcome in one way or another if we are to expect industry to help.

From the audience: There have been several suggestions that we must move across from the engineering side to the medical side – even permanently, some say. I would like to point out one hazard if we do that. If you move a man from one side to the other, then for a year or so he retains much of the value of his former associations. But he has got to keep communicating, he has got to keep going back or pretty soon he is part of the new group and no longer part of the former one. I suppose we need somebody who can be in both places at once.

From the audience: A committee was set up between Harvard and MIT to try to explore what technology can do for medicine and what problems medicine has for technology. The same sort of problems exist all across the board between two such institutions. I think one of the problems that a foundation can tackle to ensure the interface across the line is a very tangible one – the very serious problem of taking more and more engineering trained applicants into medical school. At meetings such as this, we see that the problem is one of communication between the physician and the technological discipline. We see with increasing clarity the need that Dr. Chaplin talked about, the need for measurement, but we also see the need for the ability on the part of the medical profession to state its problem in technological terms. I think an important part of this interface has to come from within the medical profession itself. One way to do this is to encourage a much larger proportion of engineering trained applicants to enter medical schools.

From the audience: There is one evil in what this gentleman has said: a doctor, to maintain currency in his medical knowledge, must continue in medicine, and the same is true of the engineer.

From the audience: It is only a matter of properly restructuring our educational programs so that we don't have this enormous dichotomy between medical education and engineering education.

From the audience: That is not the point. I am an engineer and I have to do everything I can do to keep up with my engineering. And the doctors that I know do everything that they can do to keep foremost in their fields. It might be a mistake to try to make a race of doctor-engineers. I think you have to have two separate disciplines, each with specialists in their own field, who communicate with each other and bring to bear their own specialties on the problems.

McLaurin: I would just like to suggest that modern medical practice includes a good deal more than just medical doctors.

From the audience: As an engineer listening to the doctors here and the medical community in general, I begin to wonder if you really understand the term *technology*. I think from the medical side you are looking at the engineers to come up with a black box that answers your problem. It seems as if you are looking to the engineer for solutions, and not for any assistance in defining the problem. Working with you, he can do both just as well. Also, I think that the technology that they are talking about is really that of material design. Now, we talked yesterday about a fluid of specific gravity 2. If you had a real use for specific gravity of 2.1, it could probably be designed. So we need a specification. Then we can talk together. You need to set down what your requirements are from the medical side so that the engineer can match them. Then I think you may have the solution.

McLaurin: We are running into a communication problem here.

From the audience: I just wanted to speak briefly on that engineers-doctors point. That is the path I took, to go first to engineering and then to medical school. The conclusion I come to agrees essentially with what you say. There shouldn't be a lot of engineers in the medical school, but there should be a few acting as a liaison between the two disciplines.

From the audience: I think that perhaps a lot of people are surmising that because a person is an engineering graduate he is an engineer. This is not true. And therefore, if you are going to doubly educate. . . .

McLaurin: Isn't the same thing true in medicine?

From the audience: If you are going to doubly educate people, you have to start with people who already are engineers. Now, this is going to take a lot of money, because an engineer isn't going to leave his profession and go into medicine, unless he can keep his standard of living up.

From the audience: What we are talking about is problem solving. There are lots of problems. We could list thousands of them here. I would like to go back and just comment on the business of communication. I think the medical profession needs to know what the real state of the art is. Is there some kind of Sears & Roebuck guide I can go to and look up things, people's names and so forth? Maybe some of you may remember the books on Medical Physics, I think it was called. It was a series of three volumes that was put out 10 or 15 years ago. If you wanted to know something about x-ray diffraction as it related to medicine, you could go to the appropriate volume and find a relatively brief discussion of the subject. I think we need some bibliographic source of the kind of information that is really available circulated among people. There are a lot of societies now. The Society of Neuroscience, which has just recently been formed, will have its first meeting in Washington in the fall. I don't know how many engineering people are in this particular group, but interaction in such societies would be an important contribution.

I was fascinated by the systems approach and the way in which engineers think about systems. We are not brought up to think this way in medicine. So we need, I think, some educational programs in medicine to develop people who can think along the lines of engineering systems. And also, we want to be careful in engineering that we don't make models that are irrelevant to what the biological situation really is. We need to go back continually, asking whether a model fits; where it does not fit, we must throw it out.

There are university departments of biomedical engineering that are struggling along and need help. It would seem to me that we could do something to help these departments, to strengthen them in different ways that would eventually get the idea of the interdisciplinary systems approach to the student. It is important to get the students that are coming along to develop these concepts. I know this approach is under way in many universities, but on a very small scale.

Arnold: Many of us who have been in aerospace, as I have for the last 35 years, have become rather hybrid people, and we did this out of necessity. Von Promin, for example, invented a new field, aerothermochemistry. In the early days, when we flew at high speeds, it was almost a straight mechanical problem with help from the applied mathematician. As we went further along, we found out that certain chemical reactions took place when we reached hypersonic speeds. So we retrained ourselves. As soon as we found that there was an urgency and funding available for this training, we obtained a new kind of individual. I see two groups, medical and the engineering, and I see an overlapping group, containing people like those we have trained because of our needs and available financing in aerospace.

Mann: Dr. Chaplin began to touch on a subject of education. I am glad to see the pendulum has gained some momentum. We are now solidly into education. He noted that several previous people had asserted that the patient population was very heterogeneous, that each one of the 2 million hemiplegics had to be considered an individual case. One of the problems that becomes apparent in work with engineering students on medically related problems, and in formal subjects as well, is this: through engineering and physical science education, we give to our students, because we inherit it ourselves, the great power of thinking about all physical reality in terms of a relatively few powerful laws such as those of relativity, energy, momentum, and so forth. That is how we deal with all reality, and as a result all problems of ours tend to seem very uniform. However, not only within the patient population, but at the cellular level, the variations in the biological system are enormous, and its complexity relative to the type of abstractions we used in engineering is so great that this complexity and variability must be a part of the engineer's education. Conversely, we have the problem of teaching the medical person the generalizations that characterize physical reality and that include the biological building blocks, which aren't nearly as well understood as we would like. Now, along these lines it has been noted that about 10 percent of undergraduate engineering students go to medical school. In fact the admission ratio from MIT applicants to medical school is very high, and students who know they want to go to medical school will figure it is much better to go to MIT with an 85 percent possibility of medical school admission than to go someplace else where the national averages go below 50 percent.

With respect to the interaction between Harvard and MIT and the planning for health science technology at the university, the new class at the Harvard Medical School this semester, starting right now, has an additional group of students admitted whose first year medical curriculum will be taught along a physical science line by a faculty who are very well infiltrated from MIT. Their anatomy, physiology, and other subjects, though taught in parallel with the Harvard curriculum, will introduce much more science-based material. I agree with Dr. Hambrecht that the road to a double doctorate is a very long and difficult one. But that doesn't say that medical education could not include a greater understanding of the physical laws that are fundamental to science and engineering, or, conversely, that graduate engineering training should not include more about the biological complexities.

Berenberg: As you know, the Subcommittee on Education and Curriculum is expanding well beyond the first year in terms of its planning. And people who finish their residencies are going to participate. All of us who have worked with the curriculum are tremendously excited about this possibility. I think it is going to have to catch on in many places nationally, and there are other places that are ahead of us.

McLaurin: I think we started out by talking about the heterogeneous nature of the population. In addition, each of the individuals responsible for a patient's care – the various therapists, doctors, nurses, and so on – can have a different idea of what you should do for the patient. That doesn't make the problem any easier.

From the audience: Another aspect worth mentioning here is the development of the tools to measure and solve the problems. I think Dr. Berenberg expressed an interesting development in thinking when he replied that the exoskeleton would be something to restrain a spastic patient. I was very excited about Dr. Chaplin's story because he was developing an exoskeleton used as a tool for measurement. I think one of the big potentials is an exoskeleton device that is used as a measuring system. Further it can introduce experimental inputs to the patient and note differences in performance. Also, it is even possible for the computer to interact and optimize the inputs to the patient, analyze characteristics of the cycle of inputs, and perhaps discover how to help the patient in that way.

Mannarino: We are listing at this Conference a tremendous number of problems, and as a physician I have many that I could list on the medical side. I would like to hear some positive recommendations now that will make this meeting constructive. Otherwise, we will all go back home and wait for the minutes, and it will be very hard to get together again. Maybe it will take six months or a year before we can do it. We need an advisory group, that will take responsibility for communicating back and forth, with some appointed officers. The only positive recommendation came from the Clinical and Engineering Group – isn't that the name of the group that made some guidelines? I don't think we should be allowed to leave this room without some positive guidelines as to what we are going to do next.

McLaurin: Are you going to talk about that?

Mannarino: Well, I think my point is relevant. The point has been made abundantly clear, and I think we all buy it, that NASA's problem of going to the Moon is different from the problem of individualizing care for so many patients with this heterogeneity of different kinds of problems. However, I think it is a fallacy to conclude that because of this heterogeneity, each and every engineering solution has to be, from start to finish, a separate project. Look at some of the very successful large-scale engineering solutions like the automobile, the telephone, the digital computer. These are all things that are quite specific and manufactured on a large scale. Yet they are adaptable to a great many different users' needs. Once the device is engineered, its adaptability is built in and the user adjusts it to his own needs. What I would like to dream about is a set of tools that can be developed and manufactured on a fairly large scale, but nevertheless are adaptable in clinical use. This is what we are lacking to some extent.

From the audience: Well, I will speak to Dr. Mannarino's suggestion, and also comment on what Dr. Nashold said about the use of systems analysis of disease problems. The single disease has a problem that needs a solution. Systems analysis has been used in trying to assess viruses as a cause of leukemia, for example. A great deal has been done in this area. I have used this approach many years in examining the problems of the Neurological Institute. We are working on an overall examination of the mental retardation problem and the HEW's efforts in this area, based on this kind of analysis, defining the problems and how they work up to the solutions. When you make a systems analysis for your little box, or cure, as you put terms in, they have to be specially designed. *Cure* in this sense means all therapeutic maneuvers, whether mediatory or whatever. For something like cerebral palsy or mental retardation, which is a result of many things, the box that might be called "cure" includes all the rehabilitation and other special educational activities. And in attacking these problems of helping the neurologically handicapped, we must sit down and really examine the problem and all the special subsections of it.

Arnold: Thank you very much, Dr. Frank. I would like to call now on the engineering side of the house, Dr. Reswick, to give your opinions and get a discussion started.

Reswick: As an engineer speaking to a large group of engineers, I really have nothing specifically to add to the very large number of points that have been made with respect to the techniques of engineering. (At this point, Dr. Reswick told the audience his "Parable of the Priests and the Gnomes," which is published in *Biomedical Engineering*, 6, 366-368, 1971, under his name.)

From the audience: We don't have much time left, and we can dissipate our energies by expounding on the problems further. I would like to see if we can't come up with some specific suggestions as to where to go from here to deal with the problems. I think we are all well aware of the existence of the problems.

From the audience: I have been working in the engineering and die-operating business for 18 years, and I have been attending many kinds of meetings like this. I see through the years a greater potential for a synergism here.

I like that remark about locking the door until we get an answer. There should be a steering committee of some sort. We need a definite set of goals. I know from experience that with a goal that is too ambitious, the whole program is lost. We need small measurable steps of progress. We need to set a good path and then have noncontroversial benchmarks of progress. Ask, did we do it or didn't we? And if we did, we will act accordingly. A team in the steering committee should have some coordinators, technical and medical people, and they should define the problems, pick the appropriate experts, set the goals and methodology, and then solve the problems.

Reswick: Again, we must confront the problem of deciding what needs solving and what resources should be devoted to the solution. A good example of the pitfalls we can encounter is the artificial hand. For perhaps a hundred years, perhaps much longer, engineers have been fascinated with the human hand. They have assumed that if one could produce a mechanical equivalent, it would be a boon to mankind. And in the last some 10 years or so, there have been a large number of efforts in other countries, including Germany, Yugoslavia, Russia, England, Japan and Canada, where groups of engineers have assumed that a likely candidate is the unilateral amputee, the so-called below-elbow amputee, whose hand is gone but who has a forearm. The fact is that an amputee without one hand can carry out at least 85 percent of his activities of daily living. McLaurin wants to put it higher, maybe 95 percent. That means you start with a 5 to 15 percent margin of improvement. The next thing is of that 15 percent, probably half deals with cosmesis – the extent to which the amputee given a lifelike hand is made happy in terms of his own personal goals. So that leaves about 7 percent of the total problem available for engineering solutions, and yet tremendous amounts of energies from engineers and associated scientists and physicians have gone into highly sophisticated electromyographically controlled hands. Probably half a dozen are now available, and the number of these actually used by amputees is very, very low. Furthermore, all these sophisticated, myoelectrically controlled hands still have a long way to go to achieve the performance of a body controlled hook. The moral is obvious, I guess.

From the audience: I think that observation bears a lot on what we have talked about. It is easy to assume that such a use of numbers is correct and I think this is one of the areas where we have a serious problem, namely, when we talk about compensatory efforts on the part of an individual who has a disability. He puts into the measurement scale a great deal of effort or ingenuity in concealing his deficit. I believe somebody has reported that Pasteur himself had a massive loss in one cerebral hemisphere, but it was not obvious. Similarly, when we use a rudimentary method of measuring what it is that a person does, let's say with his hands, or with his eyes or with his ears, we may get on that scale an 80 percent or 90 percent or even 100 percent measurement. I think we are dealing with what the engineer would call a "nonlinear system." Such a use of numbers is a scale, but it is inappropriate because it comes up with an apparently paradoxical situation in which a difference doesn't seem to make a difference. I think technology has a great deal to contribute to the business of measuring rehabilitation; a great deal of sophisticated thinking developed by engineers for dealing with nonlinear and nonstationary problems is extremely appropriate here. I am sure that someone like Professor Young can tell us it is very hard to inject this type of sophistication back into the problem – that is, when we try to re-examine the problem so that such concepts can be applied, a very basic re-examination of the basic facts of the performance is necessary.

Reswick: I agree completely with everything you say. For me, it is an issue of priority. How do we allocate scarce resources of time, talent, money, facilities? In which problems can these scarce resources really make large differences? I maintain that this is a very important issue.

We are not going to solve any problems here, but we must decide from this point what to do next. It was noted that we are all going home, and there is going to be a fairly quick dissipation of thinking with reference to this particular meeting. We need to decide how to continue the momentum of what I think has got us started here.

Arnold: Thank you, Dr. Reswick. I would now like to call on Dr. Melvill Jones to continue the discussion, with particular reference to the neurophysiological aspects.

Jones: It seems to me that we have come up with what might appear to be two independent and unrelated objectives: first, to try and establish ways to bring different sources of expertise together in their application to single tasks as a general working tool or approach to progress; second, to generate specific ideas of where real progress could be made by the use of NASA's expertise in the field of neurology and rehabilitation today. They seem to be miles apart, these two, but I don't think they really are. The question is how these two aspects on the one hand can be positive in their own interests and on the other hand can be brought together. Engineers are not fundamentally different from medical men. I know: I have lived in the two environments. But I do find that some of the medical members of our teams tend to view the engineer as a kind of servant to the medical man's problems. In my experience, this is not the way real progress is made.

In addressing the question of how to bring disciplines together, we are faced with two problems. One is to bring identifiably diverse disciplines together by some means; the other is to generate new channels of teaching that will bring pathways together in single individuals and groups of individuals. I teach medical graduates in neurophysiology, and I find that during that first year of undergraduate learning, there is a tremendously broad enthusiasm. Everything is exciting, and whatever the student's background, he is open to all kinds of suggestions and opportunities. I suggest that it is at this stage, at least in the biological sciences and particularly in medicine, that we should introduce in a realistic, but not too sophisticated way, the values associated with quantitative appraisal of biological factors, and attempt to quantify clinical conditions as well as one's progress in treatment and diagnosis.

One could ask an engineer to address premedical men in their first year. This appears, on the whole, to be a poor approach. For one thing, it is very difficult to find the right man. For another, the engineer will tend, by virtue of his training and separation from medicine, to concentrate on his personal views and "pet" projects without relation to medicine, whereas his audience comprises individuals whose training is primarily biologically oriented and whose goal is to take a medical degree. It is very important, however, that the students are not left at the end of the first year with the fearful feeling that any engineer who touches medicine is making a mess of it.

Some of my best graduate students are introducing new observations to make it clear that quantitization in bioengineering, engineering or mathematical biology, biophysics, or biochemistry, has important values that converge on medical problems rather than diverge from them. An interesting question for discussion is, how much effort should we expend in organizing teaching to introduce good quantization at the expense of some of the classical teaching of, say, anatomy and biology?

The training of graduate students is the next hierarchical level to consider. I find that what you put into your undergraduate students very quickly feeds back into the postgraduate or graduate student areas. In my research unit, we have one engineer who graduated with a Ph.D. in aeronautical engineering, and came out with the best Ph.D. in engineering physics for the year. He elected to come to us in neurophysiology as the best way of realistically applying his new-found expertise – not just as an aid, but to be as real a participant in the biological sphere as he was in engineering.

On the other extreme, I have just taken on a physiotherapist who had a special interest in physiology and neurophysiology and who had done outside courses that were equivalent to those in our basic physiology program. We are updating her training in neurophysiology and her program is a study of neurophysiology of spasticity. She is going to look at this in really a realistic way and has gone to the point of acquiring patient know-how, a realization of the problems that patients encounter. She will use her basic neurophysiological ability to gain a further understanding of the clinical condition.

The next stage seems to be choosing fields for research. One of my particular areas of interest is very close to that of Dr. Larry Young's. It has been a real education to work for five years with an electrical systems engineer, John Milsum. In the first year of our working relationship, we were rather skeptical of each other. Over the next two years, we began to learn a little bit of each other's expertise, but we didn't really value each other's judgment. For example, at one point we were listing the single nerve cells in the brain stem and trying to gain their informational content – their message in relation to outside mechanical stimulation of the balancing organs. The engineer said, "Well, I don't care really where the recording electrode is; what we really want to know is what the information is doing, what the informational content is." It happened that a famous neuroanatomist was present, who said, "But my dear boy, if you don't know where it is, the whole thing has got to be done again because we have no knowledge of what part of the wiring diagram you are looking at." The answer was that we had to do both. And this is what we have to learn to be able to do.

This experience points up some questions that should be discussed; for example, in what ways can we promote interdisciplinary interactions by training, and where can we find specific mission-oriented programs in which the engineers can start to apply their expertise? In all the talk at this conference, no one has suggested one of the mission-oriented goals that could generate a NASA contribution.

I would like to see a number of goals spelled out for discussion. One that has been right in front of us all the time is the development of a exoskeleton with the specific aim of learning to drive it to the extent possible by our own motor system, which means introducing neural and biological control. Another might be the use of NASA expertise for pattern recognition, in its broadest sense, to devise characteristics of known diseases in ways that haven't been done before. The obvious one is Parkinson's disease, in which we think that little-understood mechanisms are significantly involved. Available pattern-recognizing capabilities enable us to guess at the kind of mechanisms in the brain that could be contributing to this disease process, but at the moment it is mostly guessing. I believe we really could make hard, matter-of-fact progress in this area.

A third goal would be an understanding of the neurophysiology of spasticity. You can try to teach the neurophysiology of spasticity to medical students, but you don't know what the cause is. I think as soon as we know what the causes really are, we can begin to search for objective ways of treatment.

The last objective I would like to mention is to acquire optimization in health care through systems analysis. This is an active field in which the least-cost pathways for diagnosis and for treatment are being sought. Once the diagnosis is made in a really objective way, it is possible to search for criteria and model the pathways by computer programs.

So there are four suggestions for objectives that might constitute a goal.

Arnold: Thank you, Dr. Melvill Jones. I think it is important that we come away from this meeting with a few concrete items, so that when we get back home and are searching for additional support, we can point out that these are areas that might be successful. However, I don't think we can come up with priorities at this meeting. One of the important things that NASA can do for us, and possibly Dr. Wyatt can help us here, is to show us how they have gone about determining the important missions, how they team people together to attack these missions, and how they arrive at priorities and give momentum to an effort.

The "Wood's Hole" type of conference is a procedure in which I have been somewhat involved on a few occasions, and I know it has been used by the Department of Defense, NASA, and the Air Force. As one example, an earth satellite that hopefully will be in orbit very shortly may have been introduced as a concept at a meeting of this sort.

Dr. Wyatt, do you have any comments about NASA procedures in the areas noted?

Wyatt: The kind of conferences you refer to as the "Wood's Hole" conference have been a vital part of the formulation of the NASA program. We don't take the view that we should decide unilaterally what should be done and what shouldn't be done. When we are dealing with the space sciences, for example, we assemble the practitioners of science in these kinds of conferences, obtain their views, and are then guided very heavily by the objectives that they enunciate as important and the priorities that they attach to those objectives. The same approach is followed in what we call the field of applications, as we try to get the representative community concerned with the particular applications to express their views.

I detect here the common characteristic of an open discussion where we fluctuate between the very broad and the very detailed aspects of a problem. We talk about why a particular system solution won't solve everyone's problems. I think that this is not a profitable function for a group of this sort. It is more profitable to look at the broader picture. I want to suggest one viewpoint that is neither that of an engineer nor of a medical doctor, but the view of the government administrator.

Somebody noted earlier that there was a peculiar set of circumstances that enabled the NASA program to succeed. (Incidentally, I think most of you have connected NASA with Apollo; NASA is much more than that project alone.) Some people believe that these circumstances are not going to arise again. I strongly challenge that idea. We in NASA think that one of the lessons from the space program that people should learn and act on is very fundamental; that is, that a society determined to accomplish something can do so if it is willing to organize and to support the activity it has in mind, and that no matter how immense and enormous the task appears, it can be accomplished; furthermore, it can be accomplished in the open, with long advanced notification of what will be done, and with clear criteria of what the hallmarks of progress will be. I think that President Nixon's statement shows that there is an awareness that this lesson has begun to take. People have a right to demand of all elements of their government, I think, the same characteristics: state what you are trying to do, how you are going to get there, and what you are going to see as the hallmarks of development; then, hold your government responsible. I think President Nixon's recommendation that science and technology is brought to bear on the real problems means that we must try to identify problems in some terms and discuss realistically which of them is susceptible of solution over some period of time. We may not be talking about solving the problem of 2 million cerebral palsy victims in five years, but maybe we could talk about solving the problems of 100,000 or 200,000 to start with. If we took a piece of this problem and applied the proper organization – and I think the key here is the proper organization of effort – it could perhaps be solved. If you can identify what is needed and can be accomplished, and a way of accomplishing it, I think the prospects are not unreasonable for getting the support from our society that it takes to achieve the objective. I don't think we can resolve here today just how this ought to be done, but I do think that there are techniques available. I don't think that giving the problem to NASA is the answer at all, but I do think it is profitable to find out how NASA and DoD have attacked their problems. These approaches could be applied to new problem areas to find out what kinds of organizations, goals, and teams are needed to do the job. I personally am convinced that NASA's success lies in its use of a team approach to a problem. We deliberately try to construct our teams with the proper mix of the requisite disciplines and then say, "Here is the problem, work on it as a problem, and not just as an exercise in disciplinary excellence."

Arnold: Thank you, Dr. Wyatt. This is the sort of advice I have been trying to pass on to the United Cerebral Palsy Foundation. We are hoping that we can begin with the help of those of you who have been deeply involved in some of the problems that have been discussed at this conference. Now, United Cerebral Palsy is going to try to approach people in various agencies in Washington to get support and advice. I know it will be available from NASA and I am sure it will be from the other agencies. Now, could some of you – Dr. Mann, for example, and others who have had experience in this area – give us some guidance here? We plan to call on you in the future for your very intelligent approaches as to how one goes about constructing a plan. Dr. Berenberg, do you have anything to add to this?

Berenberg: I think there is a rule for the voluntary health agency in putting the pieces together, and doing precisely what you say, and I don't think it ought to be limited to United Cerebral Palsy alone. I think that one can reach out into the related voluntary health agencies, which, as you indicate, represent the voice of millions of concerned citizens of the country. The hard fact is that it is going to take a lot of dollars. We would hope that the dollars will be available, and I would trust that collectively we could decide how they would be spent most wisely and most directly. I think particular attention should be paid to the matter of priorities in terms of listing which thing you would do first. Each of us tends to have the prejudice of wanting to explore what we are working on at the moment, and I think priorities are something that certainly we are going to need some help with. I think that a start could be made by the United Cerebral Palsy, but they could not do it alone. We should obtain the assistance of the various federal agencies represented in this room, each of whom may be reluctant to take the full responsibility alone. This type of planning has been effectively done by voluntary health agencies in the past, and could be a logical next step.

Arnold: Dr. Billingham, do you have any comment?

Billingham: Just to support some of the things Dr. Wyatt said, and perhaps to answer your request for specific suggestions. There is no question that the technique of assembling working groups, often under the auspices of the National Academy, have been extremely effective in establishing program plans, based on the demonstrable needs and priorities of key areas identified by the top people in the various disciplines. The space astronomy program is a classic example of how a very clear-cut program plan can be developed in an area in which planning is very difficult because of its fundamentally scientific nature. So I would like to endorse the suggestion for a "Wood's Hole" type of meeting. Perhaps the Academies of Science and Engineering together could set up a three-week conference. . .

From the audience: . . . and the Institute of Medicine

Billingham: And the Institute of Medicine, thank you, . . . that would be held for the purpose of formulating some very specific recommendations. I think this would have to be supported on a joint agency basis, perhaps spearheaded by HEW, and that a group like United Cerebral Palsy could be instrumental in bringing the whole thing about.

From the audience: People who actually work with palsy victims have a broad picture of the terribly complicated condition that it is, and have all kinds of neurological tests and other ways of evaluating particular disorders. However, the problem is so complex that when you try to present it to someone on the technological side of the fence it is rather like trying to prevent cancer by showing an endless number of tumors on slides. It seems to me that one of the most constructive things that the United Cerebral Palsy Foundation could do would be to devise some way to progressively pull together a body of basic material, as NASA has done in certain areas. For example, let's suppose they want to solve the problem that involves building a suit for someone. They pull together a very basic set of measurements, find out what is known, what is most relevant, organize it, assemble some formative data, and integrate the pieces into a body of information from which an intelligent group of technical people can extract a specifiable problem. In the case of the cerebral palsy victim, one difficulty faced by the engineer or technologist attempting to make a contribution is the lack of a sufficiently specific definition of the problem. We don't want to know all the theories on how the condition arose. Neurological scientists and others who feel they have a responsibility toward these victims need a very ordered presentation of the problem itself and then a progressive interaction with the technological community in an attempt to say, well, now, what can we do to make the problem clearer, to specify the problem more succinctly? Can we prepare such a body of material, rather than say that cerebral palsy is something you will just have to get familiar with by going to an institute and looking at a lot of patients?

I would like to just give one small example of this problem in the medical field. If you want, let's say, to move technology into the area of anesthesia, one of the first things that has to be specified is what the anesthetist does in the administration of anesthesia. One of the things that the engineer would immediately see is that it would simplify the quantification of the problem enormously if he could impose an automated barrier between the doctor and the patient, so that the doctor, in order to do something, had to make a specifiable demand.

Arnold: Dr. Berenberg, do you think you could respond to this. Can this sort of thing be done for cerebral palsy? I think you have pointed out that it covers so many facets that it is not that easily identifiable in this analytical fashion.

Berenberg: Oh, I think it can be identified. I could spend the next five hours identifying 500 aspects of it. If you ask what are the priorities for cerebral palsy, I think that one of the priorities, as Dr. Chaplin said, is being sure that what you are doing is related to what happens afterwards, in terms of an evaluated treatment. The number one enemy at the moment is what happens to the premature baby within the 48 hours after he is born. I think that five or six of us could sit down and map out an attack in terms of how one studies this. We know that the incidence of cerebral palsy is 80 times higher among those that are born weighing 4 pounds or less. If you want to know what measures will be used, in the case of the hemiplegic, we could go on and on and on and still couldn't cover all the complexities of the situation. It would be easy enough to map out those that are the most important statistically, and also those that hold forth the greatest promise of making an immediate impact. They don't necessarily equate.

Arnold: I think it is time now that we close our conference. Do you think there is anything more we should cover, Dr. Billingham?

Billingham: No.

Arnold: I want to thank NASA, and I want to start with the Administrator – I hope you pass this on to him – who was very kind to arrange my first visit here. I recall when I had my first meeting, there were a number of people who attended our conference and there was a great deal of pessimism that there could be an interaction between the groups or that there could be any problem areas that might be suggested. In contrast Mr. Dimeff pointed out today that the response that we have seen at this meeting here has made him feel that it has all been worthwhile. I definitely feel that way. And I repeat I am going to call on a number of you for advice as to what we do in the future. And from my standpoint, this is just the very beginning.

Berenberg: The future is tomorrow.

Arnold: The future is tomorrow.

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