Man, Mechanism, and Mobility: Bioengineering

Ἐν ἀρχῇ ἦν ὁ Λόγος : "In the beginning was the word . . ." according to St. John, and perhaps it would be a proper beginning to offer a formal definition of the term Bioengineering. We shall refrain, however, since much of the meaning we intend to convey is obvious from the mere juxtaposition of bio and engineering. To define it further would impose limits on our appreciation of the scope and potentiality of the issue to be expected from a union of physics and biology, engineering and medicine.

The trend to consider research and development simultaneously from both human and mechanical standpoints can be noted in many recent and current research programs. Space exploration, for example, must proceed in terms of the limitations and capabilities of both primary factors: the man as well as the machine. Appreciation of the human factor in the man-machine equation has become increasingly vital in military research. On the other hand, medicine and physiology primarily concerned with biological processes are increasingly dependent upon the development of improved instrumentation. But this is an old story in prosthetics and orthotics where, as perhaps nowhere else, the limitations of engineering science and the complexities of human disability combine to impede advancement. Most promising in this respect is a systems analysis approach in which physiological and engineering concepts, intimately related in a common frame of reference, are focused on problems of human disability.

The Veterans Administration has long recognized the value of systematic research and began to organize such efforts in prosthetics and orthotics 15 years ago. Other agencies of course have since contributed to the same objectives. The results in this field have kept pace with scientific development everywhere and it is generally conceded that more has been achieved in the last 15 years than in the previous 1500 years. But goals in this respect have not remained static; although progress has improved the lot of the handicapped, increasingly higher achievements are demanded and sought.

Future advancement requires both the improvement of present concepts and the evolution of new ones. Improvement can be achieved by the refinement of present techniques; innovation calls for the introduction of new ideas to provide a breakthrough in design. Both avenues of progress must be based upon adequate research and evaluation systems.

In keeping with its tradition of leadership and its responsibility to offer the best service possible to veterans, VA has taken steps to meet these challenges. It has very recently organized the Bioengineering Laboratory, a major division of the VAPC, in an effort to consolidate its resources and increase its capacity for research and development.

Facilities

The section of the Bioengineering Laboratory specializing in human factors research occupies an area 76 ft. x 66 ft. providing 5,016 square feet of floor space.

It is located on the street-level main floor of the building providing easy access for wheelchair and crutch-using patients. Completely girdling the main floor is a mezzanine with 2000 square feet of additional space.

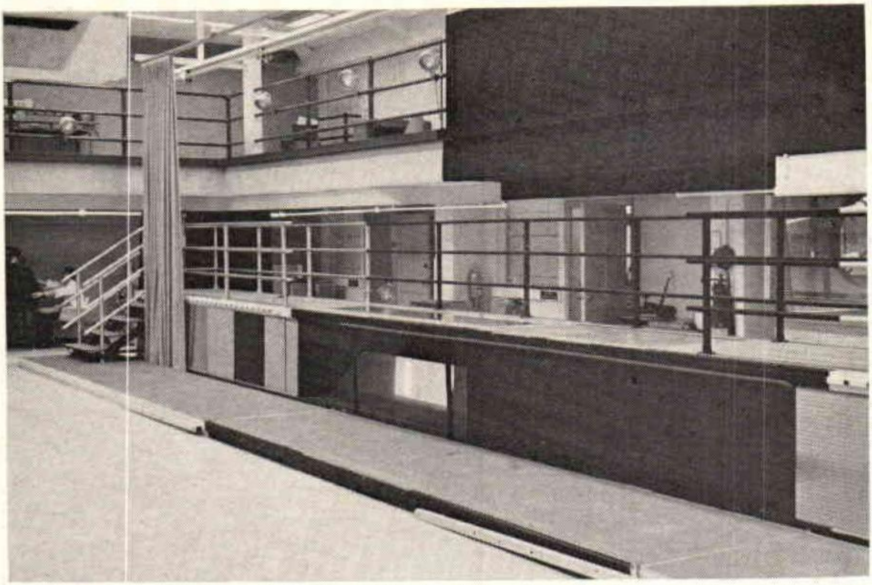

Figure 1. The main floor of the Bioengineering Laboratory showing several walkways used in laboratory studies.

On the main floor are several specially designed walkways which are used in studies of locomotion. The lower walkway, 50 feet long, has been equipped with a metal conductor tread for use in studies of the temporal factors of gait. Metal electrodes, attached to the subject's shoes, close a circuit when they make contact with the metal walkway permitting such primary gait characteristics as stance time, swing time, and velocity to be recorded. Other significant variables such as ratio of swing to stance time and ratio of step times are derived from these basic data.

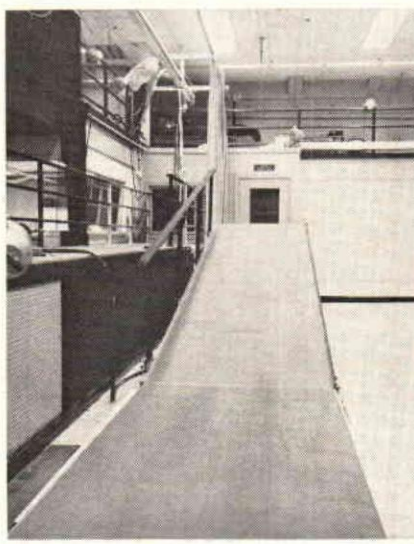

Figure 2. Electrically powered ramp permits the evaluation of patient performance in ascending and descending hills with varying slopes.

The center section of the lower walkway, 18 feet long, can be raised or lowered from either end by means of an electrically powered jack installed through the flooring beneath. It provides inclinations of up to 14 degrees and it is used to study the effects of various prosthetic and orthotic devices on the ability of a subject to walk up and down hills.

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The upper walkway is equipped with an eight foot long gridded glass

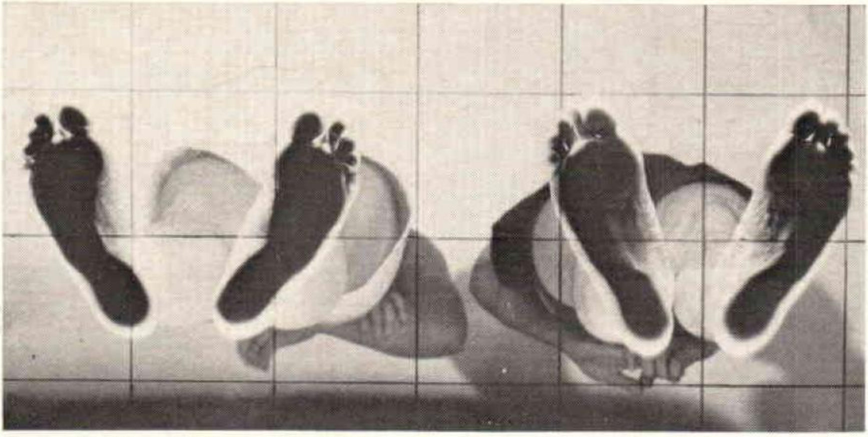

Figure 3. Glass Walkway: Density differences in the photographs obtained through the glass walkway indicate pressure patterns between the foot (or shoe) and the floor.

section and a mirror mounted beneath it at an angle of 45 degrees to the vertical. With this arrangement it is possible to photograph the interface between the foot or shoe and the floor in order to study the weight transition during the stance phase of gait.

Also installed in the upper walkway is a pair of force plates, which are used to measure the several kinds of forces interacting between the foot and the ground during stance: vertical, shear, and torque forces.

Many of the studies conducted in the Bioengineering Laboratory require the simultaneous recording of several rapidly changing variables, a task which depends upon the use of complex electronic instrumentation. All the electronic outputs are fed into appropriate amplification and recording apparatus housed in the instrument room, a glass enclosed area permitting observation of the entire Laboratory testing area. Equipment for

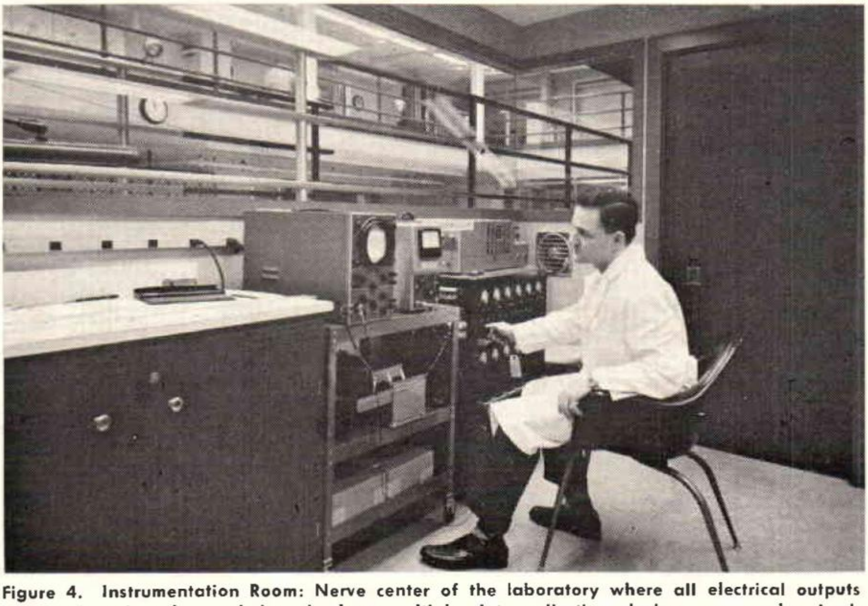

Figure 4. Instrumentation Room: Nerve center of the laboratory where all electrical outputs are monitored and recorded and where multiple data collecting devices are synchronized.

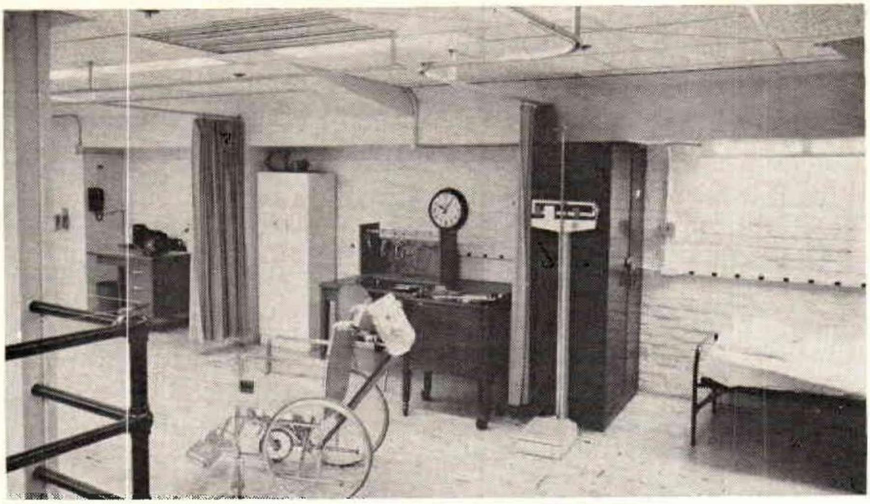

Figure 5. Part of the metabolic laboratory located on the mezzanine where space is also furnished for graduate engineering students assigned to special individual projects.

maintaining a relatively stable atmospheric environment has been installed here.

Above the main level of the Bioengineering Laboratory is a mezzanine which features a 172 foot long rectangular track. The track has been designed primarily for metabolic studies of the energy cost of using artificial limbs, braces, wheelchairs or other devices under more natural conditions than are possible on the walkways alone. A device has been installed to aid in controlling cadence and velocity during these studies. It consists of a light cable which is drawn through pulleys along the outside rail of the track by means of a variable speed motor. The subject adjusts his speed to keep up with a signal on the cable. Access to this area is provided by a flight of stairs from the main floor and by a separate entrance at the level of the mezzanine.

EQUIPMENT

The Bioengineering Laboratory is equipped with a variety of devices for recording and analyzing the major parameters of locomotion and other physical activities. The primary instrumentation consists of a pair of force plates and a cyclograph. The force plates are 15x20 inch aluminum platforms set flush with the walkway surface. Each plate is supported on four columns which are instrumented with strain gages. When a subject steps on a plate, forces of varying magnitudes and directions are applied to the plate during the entire period from heel contact to the instant of

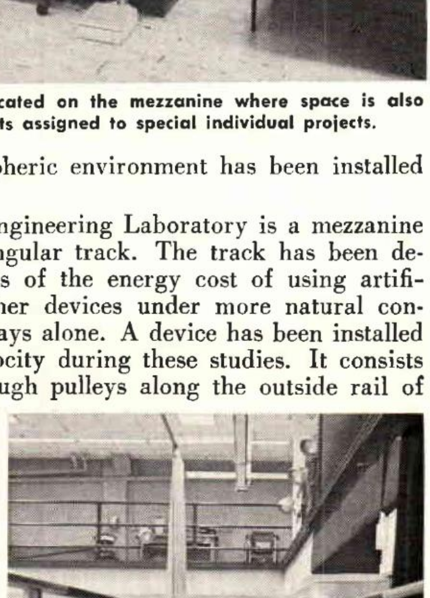

Figure 6A. Force Plates: Rigidly constructed of heavy gage aluminum and mounted on concrete and cork base they respond with extremely small deflections to floor reaction forces.

toe-off. These forces are transmitted to the supporting columns and the strain gages which are part of a Wheatstone bridge circuit. The gage outputs, calibrated in pounds of force, are amplified and recorded. The gages are arranged in a geometric pattern to respond to vertical forces, fore and aft shears, medio-lateral shears, torques and by analysis, instantaneous centers of pressure are determined.

Used in conjunction with the force plates is the tachograph, a device for measuring the linear velocity of the subject's center of gravity as he walks. It consists of a light webbing waist belt to which is attached a light cable. It is adjusted on the subject at the level of his Center of Gravity

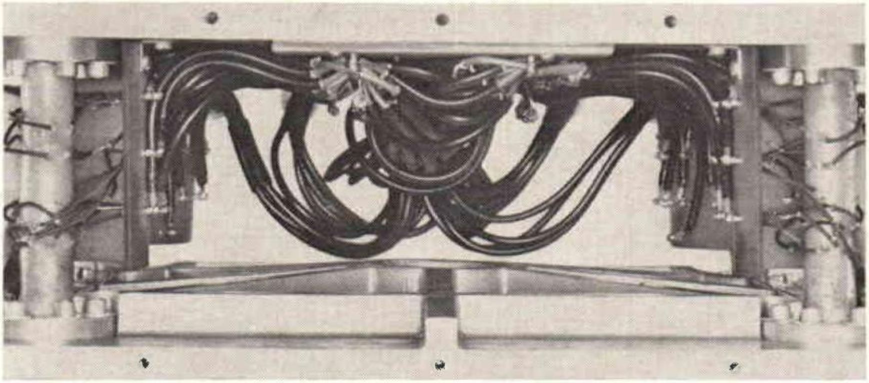

Figure 6B. Geometry of strain gage arrays mounted on supporting columns resolves component forces applied to plates.

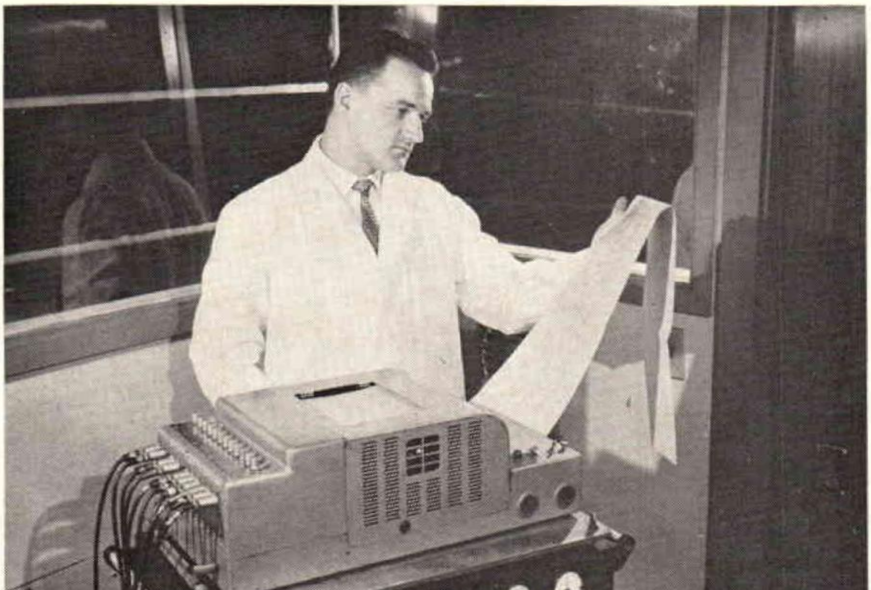

Figure 7. Twelve force plate channels record forces in three planes for each leg during the stance phase of gait. The measures obtained include curves of vertical, horizontal, fore and aft shear, medio-lateral shear and torque forces as well as instantaneous center of pressures on x and y axes.

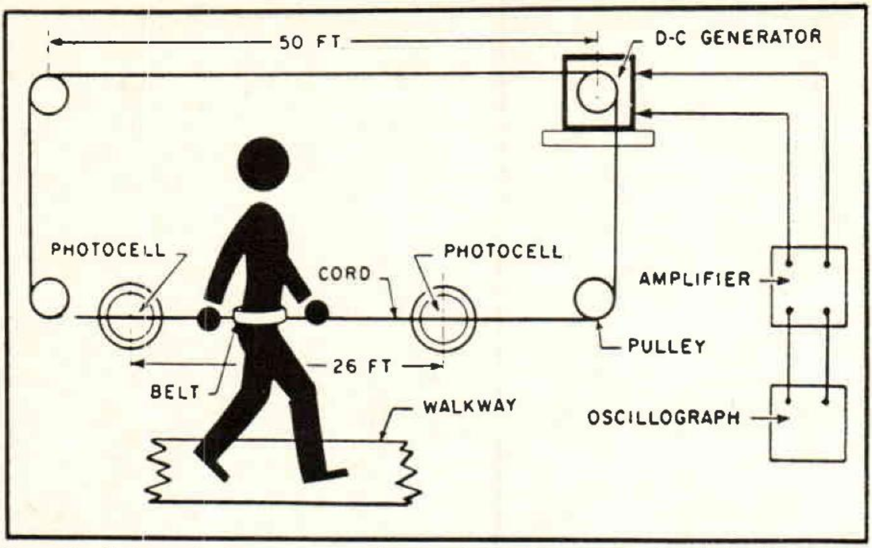

Figure 8. Tachograph: Instantaneous velocities of the CG are recorded during locomotion as a subject drives a DC generator.

(CG) as determined by weighing him while he is lying down on a large board, one end of which is placed on a scale and the other on a block of equal height; the total body weight, the weight recorded on the scale, and the length of the board are combined in a formula from which vertical height of the CG can be calculated. As the subject walks, he pulls the cable attached to the belt through a Direct-Current (DC) generator whose output, proportionate to the velocity, is recorded.

The cyclograph is essentially two cameras whose films are exposed by means of a slitted disc which rotates in front of the camera lenses at a constant speed of 12.5 rps. One camera is a static cyclograph consisting of a specially modified 8x10 view camera. With the shutter open, the film plate is exposed each time one of the four equally spaced slits on the rotating disc passes the lens, providing up to 50 exposures per second. As the film remains static, the product is a so-called "stick picture" with multiple exposures of the subject, appropriately targeted with reflective tape, as he passes through the camera field. The second camera, mounted 12 inches away in the same horizontal plane, is a gliding cyclograph, a modification of the type developed by Dr. Rudolfs Drillis of NYU. This device is similar in function to the static cyclograph, the important difference being that it transports the film in the same direction as the subject walks. The obtained photo-

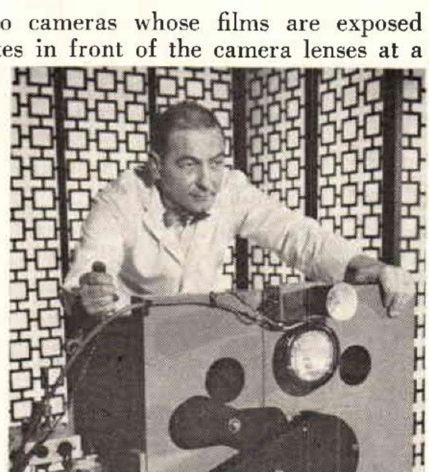

Figure 9. Cyclograph: Provides multiple synchronous exposures at 25 or 50 FPS of targeted subjects on the level walkway and on the ramp.

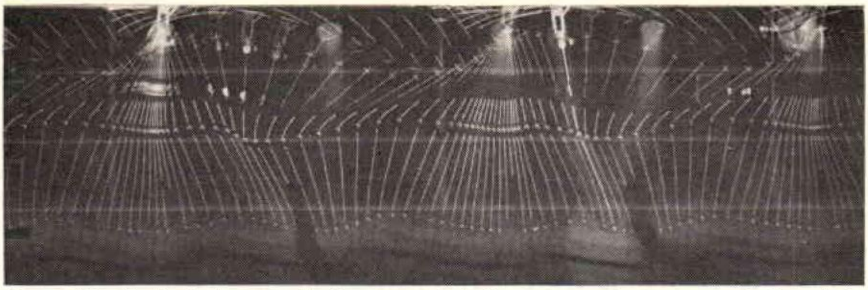

Figure 10. Static Cyclogram: Displacement of body segments in space are indicated by sequent "sticks" which are 1/50 second apart permitting calculation of velocities.

graph does much to simplify the analysis of the "stick picture" in areas such as the ankle joint where the sticks fall too closely together in the static cyclograph to permit accurate measurement.

Because a large part of modern bioengineering techniques depends upon photometric analysis, high quality photographic laboratory facilities are essential. The photographic laboratory, located on the main floor, is extensively equipped to provide these services. "Stick pictures" are processed within minutes after exposure to assure adequacy while the subject is still available for retakes if necessary. Advanced development procedures are employed to simplify analysis.

Supporting Facilities

The Bioengineering Laboratory enjoys an unusual advantage in the availability of other facilities in the VAPC. Supporting the Bioengineering Laboratory is a well equipped machine shop, an integral part of the Testing and Development Laboratory. Models, jigs, tools and components can be

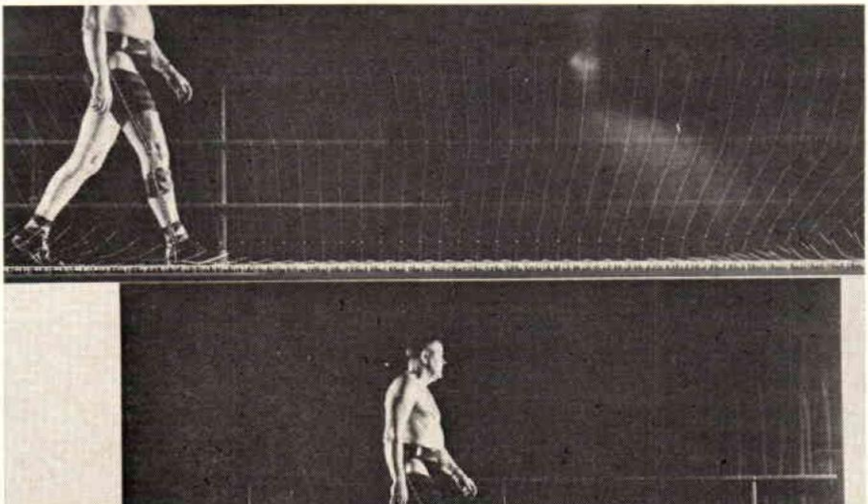

Figure 11. Gliding Cyclogram: Prevents overlapping of "sticks" particularly during stance phase.

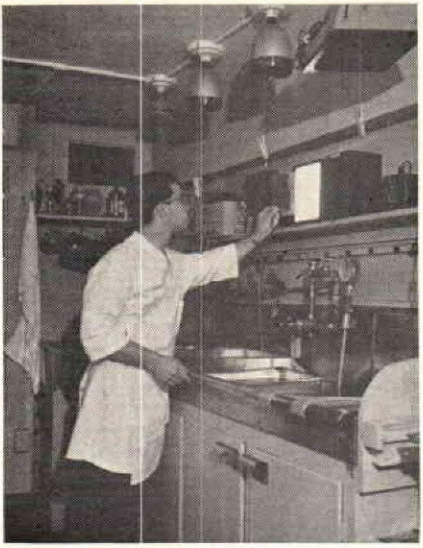

Figure 12. Photographic Laboratory: Equipped for processing stills, movies, and cyclograms.

fabricated quickly, economically and efficiently in this section of the VA Prosthetics Center.

The technique of applying experimental limbs and braces is an important aspect of many studies conducted in the Bioengineering Laboratory. As the fitting procedure is often a key factor in the research design, precision and reproducibility are fundamental requirements and it is absolutely essential that the best technological skills be available. For this reason, the Laboratory facilities include a Prosthetic/Orthotic Shop and the services of the personnel of the Limb and Brace Section of the Center.

Research and evaluation on braces also require expert technical advice on the fabrication and fitting of orthopedic shoes. The Orthopedic Shoe Section of VAPC provides assistance and support in these matters by making available highly experienced technicians and extensive facilities. This Section is also actively participating with the Bioengineering Laboratory in recently undertaken studies of the effectiveness of shoe corrections, a relatively unexplored area.

PERSONNEL

It is obvious that facilities and equipment are not the most essential ingredients of a productive laboratory; the key factor is the staff which operates the facility. As presently constituted, the full-time staff of the

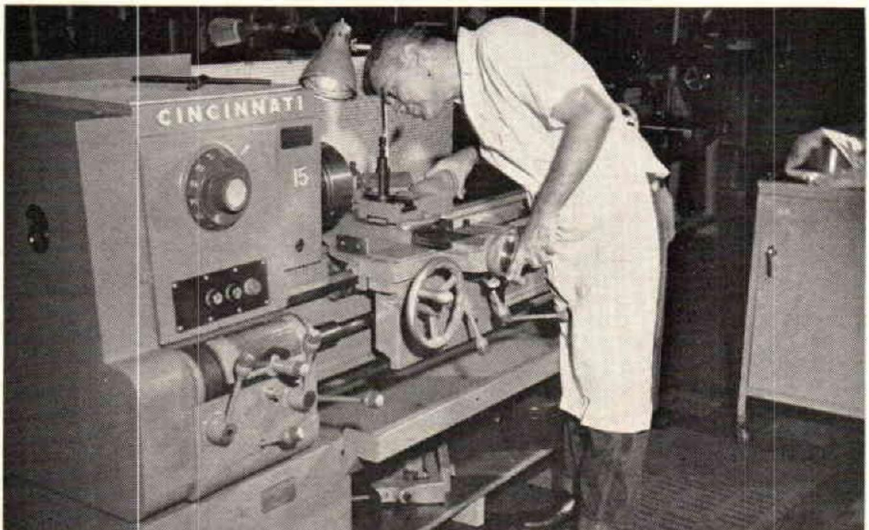

Figure 13. A small part of the machine shop: Modern equipment makes for versatility, high quality work, safety and economy.

Figure 14. Limb & Brace Section: Designed to provide the most advanced service to veterans and to improve prosthetic and orthotic devices.

Bioengineering Laboratory includes people whose primary training is in physiology, electronics, photometry and engineering. Not on a full-time basis, but available as consultants or participants in specific studies are physicians, physical therapists, engineering specialists and a physicist. This wide range of backgrounds and specialties provides versatility in research design and strong support for a variety of studies.

Activities and Plans

The Bioengineering Laboratory was conceived and organized as a center for bioengineering study; to furnish an efficient environment and modern means for research and development in this field. This intention

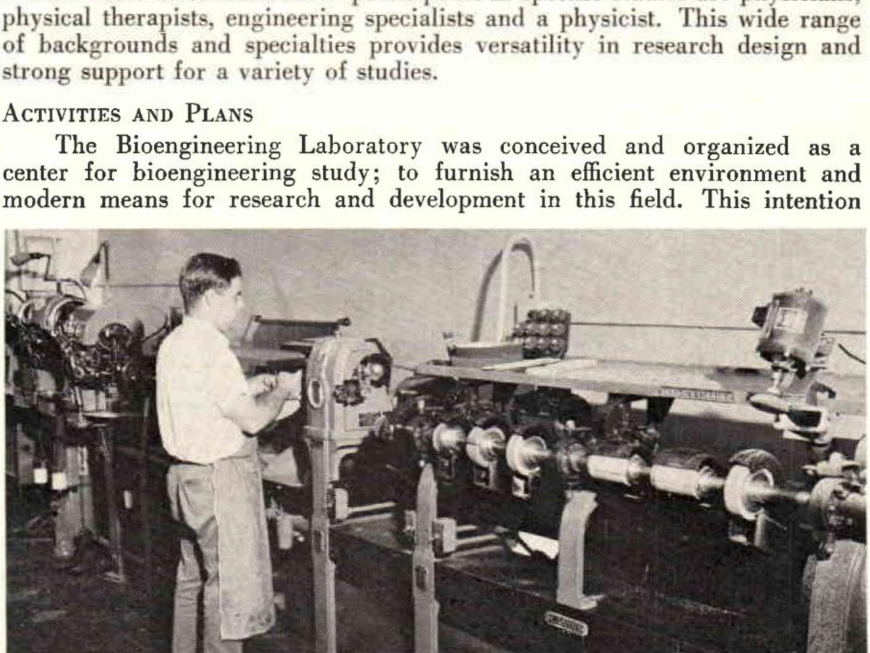

Figure 15. Part of the shop of the Orthopedic Shoe Section: Modern facility serving 12,000 veterans all over the country also provides support for research and development.

is being translated into appropriate action in accordance with a long term plan. It was devised on the basis of current needs, an appreciation of strong trends in the field, avoiding duplication of effort, and the economic exploitation of our own and others' capabilities and efforts. It calls for the development of four distinct, though closely correlated programs:

VAPC Intramural Research and Development
Cooperation with VA Contractors
Service to Other Governmental Agencies
Student Work-Study Project

1. VAPC Intramural Research and Development

VAPC is necessarily interested in an extremely broad range of problems relating to prosthetic and orthotic devices, orthopedic shoes and other appliances for the handicapped. Each of the several organic sections as well as other VA units require research and development services. These needs can be substantially met by the Bioengineering Laboratory and accordingly, the following series of studies reflecting their interests are now being undertaken:

a. Evaluation of the Effect of Several Shoe Correction Procedures on Stability, Comfort and Gait.

Mild deformities of the foot are usually stabilized or corrected by the prescription of orthopedic or modified conventional shoes. While this practice may be entirely adequate, too little is known about the actual outcome of the applications. We plan, therefore, to study the influence of conventional shoe correction practices on patient function and comfort. Conventional shoe corrections will be systematically introduced into shoes worn by normal and handicapped subjects, and the effects on their performance will be objectively described.

b. Evaluation of Externally Powered Devices for Upper Extremity Amputees.

Increasing emphasis on auxiliary sources of power for prosthetic and orthotic devices for the upper extremity creates a need for clearer understanding and a rational selection of the areas of utilization. The specific functions of the shoulder, elbow and wrist for which externally powered devices are most applicable should be clarified. Accordingly, we plan to study the forces and ranges of motion required for a variety of useful activities and to identify those areas in which external power is most needed.

c. Studies on the effect of Transverse Rotations in Normal Human Locomotion.

The purpose of the study is to fill out our present concepts of normal locomotion as regards the role of the relative rotations occurring in the tibia, femur, pelvis and spine during ambulation. Of particular interest are the relationships between the floor reaction torque forces and the displacement/acceleration of the contralateral hip joint. As an extension of this study, an objective description of several pathologic gait patterns and the accompanying muscular substitution techniques may be obtained.

d. Evaluation of Current Leg-Thigh Brace Designs.

Conventional non-weight bearing leg-thigh braces are usually constructed of two lateral uprights and fitted with knee locks. A critical analysis is required to determine areas of overdesign in strength and restraint and to improve function.

The results of this study will be applied to further development and optimization of a device offering adequate support, stability in stance phase and perhaps, some degree of flexion in swing phase.

e. Evaluating the Physical Capacities of Geriatrics.

In this field a complete program is required to determine decrements in performance with age. The work tolerance, endurance and physical educability of the aged are not completely understood. To be sought is a valid system of subject evaluation and physical conditioning to provide a rational basis for the prescription of aids.

f. Pressure Distribution Within Lower Extremity Sockets.

Several commercially available pressure transducers are being evaluated and modified where necessary, for use in this study which is of fundamental importance in evaluating the effectiveness of several currently used socket fitting methods. Of particular interest for example, is the determination of pressures on the ischium in above knee sockets, and those on the patellar tendon in weight-bearing below knee sockets.

g. Evaluation of Knee and Ankle Mechanism for AK Amputees

A definitive, long-term study is indicated in which the performance of a carefully selected sample of subjects, fitted under highly controlled conditions, will be evaluated. This study is designed to apply an objective measurement technique to the evaluation of the several hydraulic, pneumatic and mechanical knee mechanisms which are now available or in various stages of development. The ultimate goal is to improve prescription indications.

Knee and ankle mechanisms are being evaluated on the basis of several sets of comparisons. First, knee and ankle function data obtained in mechanical tests on gait simulating machines are compared to similar data obtained when used by an amputee. Then the function of the new device is compared to others with respect to its effect on the gait pattern.

h. Analysis of the Energy and Motion Requirements of a Lightweight Wheelchair.

A new lightweight wheelchair was recently submitted for evaluation. The primary purpose of the study is to compare the comfort, maneuverability, durability and energy cost requirements of the new device with conventional models currently in use. Four subjects presently using conventional wheelchairs are participating. Their subjective reactions to use

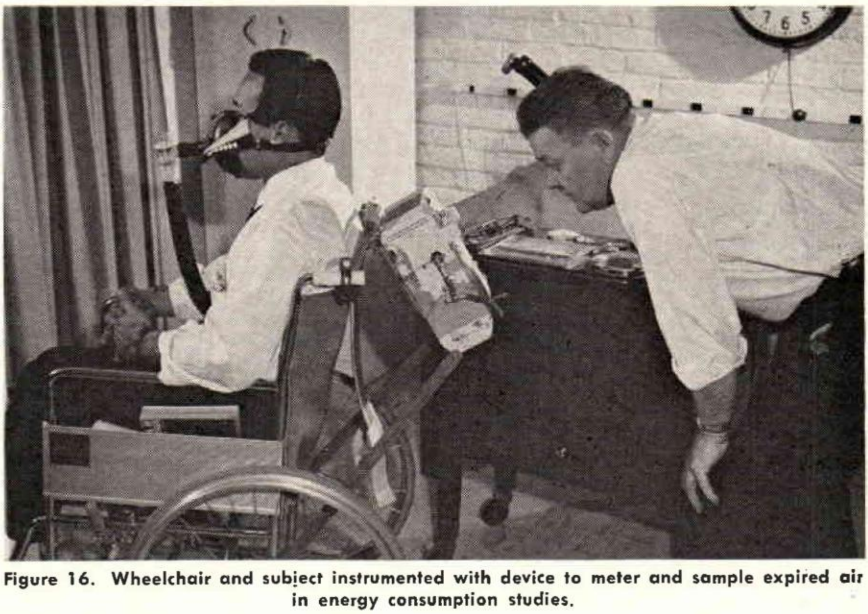

Figure 16. Wheelchair and subject instrumented with device to meter and sample expired air in energy consumption studies.

of the chair have been recorded and an analysis was made of the relative maneuverability of both items in turning corners, climbing curbs and avoiding obstacles. The metabolic costs of using each chair were determined. In addition, destructive tests to measure durability of axles, wheel bushings and framework are being undertaken.

i. Evaluation of the Single Bar Leg-Thigh (Long Leg) Brace With Limited Knee Flexion.

A leg-thigh brace featuring a single lateral sidebar and limited knee flexion has been designed by VAPC. A program is in progress to evaluate its effect on the gait patterns of several subjects. The performance of each participant in this study will be compared while using his conventional brace and the experimental brace.

j. Evaluation of the "Stand-Alone"

A mobile unit has been developed to enable wheelchair patients—paraplegics in particular—to wheel themselves about in an upright position. This device is currently being evaluated in a program to: (1) determine the ease of entering and exiting the unit; (2) analyze the design with respect to materials and mechanical adequacy; (3) determine the mechanical forces required to operate; (4) measure the metabolic energy cost required to operate; and (5) evaluate maneuverability and durability.

2. Research and Development Program in Cooperation with VA Contractors

It is at times more convenient or more efficient for the VA to assign specific programs or studies to responsible private contracting agencies or universities. Innovation and development in this field do not occur in an orderly, well-spaced progression. Rather, there are lean years and fat years in which many more devices and techniques appear than can be studied or evaluated in a reasonable time. In certain instances, other agencies have highly specialized skills which are more easily obtainable under contract than by attempting to develop them within the Bioengineering Laboratory. For these reasons, study areas involving extensive engineering services, for example, are investigated by contractors who, operating in some instances under the general supervision of the Bioengineering Laboratory, are given access to laboratory space and facilities.

An example of this arrangement is the current study by New York University to evaluate the mechanical and functional utility of the Henschke-Mauch Model A Swing and Stance Phase Control Unit. The mechanical analysis of the hydraulic unit is conducted by NYU engineers in the Bioengineering Laboratory. The biomechanical analysis of performance is also conducted in the Bioengineering Laboratory using the facilities and the equipment described above and with the assistance of Bioengineering Laboratory personnel.

3. Service to Other Governmental Agencies

Other departments of the government, notably the Vocational Rehabilitation Administration (VRA), support extensive research programs through a system of grants awarded to universities and other agencies. The recipients of such awards frequently require facilities and special services which already exist in the Bioengineering Laboratory. In order to improve economy and prevent needless duplication, the Bioengineering Laboratory cooperates in these projects. Several VRA projects, awarded to NYU, are currently being carried out with this assistance.

One example of such aid is a study dealing with the analysis of several bracing parameters. Dr. F. Rae Finley, Associate Research Scientist at NYU is evaluating the effect of ankle joint placement on the stability and gait patterns of leg brace wearers. In addition, an attempt is being made to evaluate currently used leg-thigh brace weight bearing designs.

Another example is the study of Body Parameters conducted by Mr. M. Bluestein, Associate Research Scientist at NYU. Three methods are being used in this study to measure the volumes of limb segments. In the first, castings of body parts are made in alignment and their volumes are determined by water immersion. Volumes are also determined by photogrammetry, a technique in which colored tapes are projected onto a lateral view of the casting and the areas enclosed by each grid line on the frontal surface are measured. These values are converted to volumes by Wild's contour Method. ("Surveying and Mapping," Vol. 12, April-June 1954). The third method employs a modification of Sheldon's somatotyping technique in which photos of subjects are obtained in three views and the body segments are measured. Mass moments of inertia are being determined by means of a torsion table which vibrates with a subject lying upon it, the period of vibration being proportional to the mass moment of inertia.

In certain special instances technical assistance is given another government agency for a project only peripherally related to prosthetics and orthotics. In this connection, APRL has been instrumental in developing and evaluating a protective footgear (termed SABOT) designed to reduce the incidence of limb loss due to mine explosions among military personnel. The facilities of the Bioengineering Laboratory are being employed to evaluate the effects of wearing the device (which features an "ankle joint" mechanism) on gait patterns, stability and endurance.

In a similar category was a recently completed study of an experimental exoskeletal leg harness called a Pedipulator. It was designed by the Human Factors Section of an Army research contractor as a prototype of a servo-locomotion apparatus for possible military and space applications. An investigation was conducted in the Bioengineering Laboratory to determine the effects of the device on the normal motion and force pattern of ambulation and the energy requirements for the operator.

Several other governmental agencies, in particular National Aeronautics

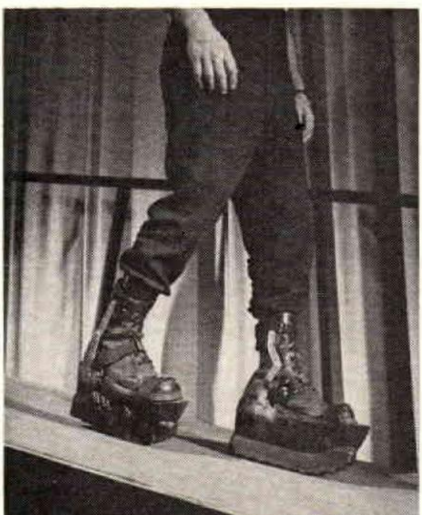

Figure 17. Sabot: Energy cost studies on injury reducing device for military use.

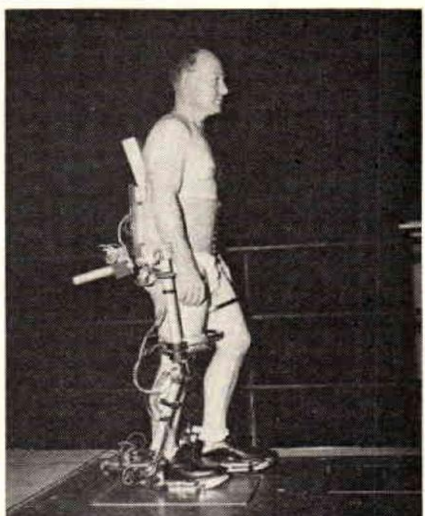

Figure 18. Pedipulator: Kinematic analysis of gait pattern using exoskeletal leg harness.

and Space Administration and U.S. Army Quartermaster Corps, maintain substantial programs of research and development. As a significant portion of these programs deal with the evaluation of human performance under varying conditions of environment, physical stress, implement use and clothing, the VA's Bioengineering Laboratory facilities may be of important service.

4. Student Work/Study Project

Currently in operation is a program in which students from several universities work in the Bioengineering Laboratory. This group includes graduate students who are matriculated in a doctoral program in which bioengineering techniques are employed. On the recommendations of their faculty advisor, they are assigned to work in the Bioengineering Laboratory on an independent study program. They gain experience by participation in data collection and reduction activities and develop the technical skills needed in their own work.

At the present time, two graduate students are participating in a joint VA/NYU Study on tibial torsion. They are obtaining data on a large sample of normal subjects to determine the ranges of normal tibial torsion and other anthropometric data relating to the ankle and shank.

During the academic year, undergraduate students also participate in the work of the Bioengineering Laboratory. Each semester several (4 to 8) undergraduate students, recommended by their professors, spend from four to ten hours per week in the laboratory, in fulfillment of a course project requiring familiarity with bioengineering methods. They learn the fundamentals of biomechanics and gain experience in laboratory methods. In the process, they perform a useful service by assisting in the preliminary steps of data handling.

The students working in the Bioengineering Laboratory during the academic year are not salaried. However, in the summer vacation period, up to six students are hired as part-time employees. These students, primarily in engineering or the medical sciences, are carefully selected on the basis of their professors' recommendations, interviews and an interest in human factors work. They become temporary employees for periods of up to 90 days at hourly rates commensurate with their background. They are directly assigned to ongoing projects under the immediate supervision of professional personnel.

The advantages of this program to both graduate and undergraduate students are obvious; they receive access to facilities, equipment, subjects and professional consultation in return for services as members of a research team in the Bioengineering Laboratory. On the other hand, they provide useful service to the Laboratory and represent a potential source of "new blood" for the field.

In the preceding sections, we have discussed the rationale underlying the organization of the Bioengineering Laboratory and we have described the equipment and facilities it contains, the people who operate the laboratory and some of the current work. In the process, we may have come a little closer than we did at the beginning of this article to a definition of bioengineering in prosthetics and orthotics, a task we avoided then as now because its full compass cannot be foreseen. We can see, however, that it is intimately involved in the restoration or improvement of volitional mobility, a fundamental process of human life. No less a task is undertaken than that of designing mechanisms to augment or substitute for human muscles and joints. While our immediate preoccupation is man, his mobility and the mechanisms to enhance it, service to the medical profession and above all to the disabled is our purpose.