validate this class of computer models for simulation purposes. The dynamic in vitro material properties and failure characteristics of the spine will be measured, with special emphasis on the cervical region. These studies will provide information for the validation of a human head and spine model to be used to investigate, through computer simulations, the prevention of head and spine injuries.

**Porous Polyethylene—Tissue Tracheal Prosthesis**

**Regular Grant: 5 R01 GM 26963**
**University of Mississippi Medical Center**
**Jackson, MS 39216**

**Barry W. Sauer, D.V.M., Principal Investigator**

The objective of this research is evaluation of three different types of composite tracheobronchial prostheses developed by the principal investigator. The prostheses will be used to reconstruct 5-cm-long circumferential defects in the cervical region of the canine trachea. The clinical performance of the prostheses will be determined by physical, radiographic and bronchoscopic examinations. These devices and bronchial sections will be removed after 6, 12 and 24 months and subjected to gross and microscopic examination. Postmortem examination of all animals will be performed. The results of all examinations will be correlated with the clinical studies, and comparisons of performance will be made among the three types of devices.

# DEPARTMENT OF HEALTH AND HUMAN SERVICES, NIH, MUSCULOSKELETAL DISEASES PROGRAM[a]

Stephen L. Gordon, Ph. D., Program Director

## BONE HEALING

**Study of Internal Fixation Devices for Fracture Healing**

**University Hospital of San Diego**
**La Jolla, California 92103**

**Wayne H. Akeson, M.D., Principal Investigator**

The objective of this research is to determine whether significant advantages can be achieved in internal fixation plates of diaphyseal fractures through the use of internal fixation devices of improved design.

One hypothesis being tested is that internal fixation of plates of reduced axial stiffness are superior with respect to the late complication of stress-protection-induced decrease in bone density (osteopenia) usually observed with traditional management. Advantages exist with respect to biomechanical properties of canine radii and femora internally fixed with plates that have large reduction in bending and axial stiffness. These results are confirmed by quantitative histological and biochemical measurements.

Early versus late plate removal is a controversial question. The second objective of this project is to study the effects of plate stiffness on the ability of fracture repair to withstand physiological loads. The hypothesis being tested is that early plate removal will prevent stress bypass osteopenia and facilitate more normal bone remodeling.

Techniques used in this study include periodic X-rays to evaluate fracture healing in the plated canine femoral midshaft osteotomies. Nondestructive and destructive bioengineering tests, quantitative histological measurements using UV light microscopy to evaluate tetracycline labeling and microradiography and biochemical analysis of the organic and inorganic matrix of bone are being used to evaluate the influence of the different internal fixation devices employed.

**Study of Bioelectrical Phenomena Controlling Bone Growth**

**Columbia University College of Physicians and Surgeons**
**New York, New York 10032**

**C. Andrew L. Bassett, M.D., Sc. D.**

This project addresses several problems in which an expanded base of applied experiments serves to improve the scope of clinical usefulness of pulsing electromagnetic fields (PEMF's).

PEMF's are currently in use for ununited fractures and fusions. Time required by treatment and degree of disability can be reduced by increasing pulse effectiveness to speed mineralization of gap tissues and to augment the osteogenic phase of repair. In this study, effects of PEMF's on improving bone graft incorporation and fresh fracture healing are assessed. Return of mechanical stability in the nonunion, grafting, and fracture studies is monitored by a new, nondestructive, noninvasive sonic frequency testing method. These results are then correlated with mechanical testing and strain gage data to determine the ability of this new frequency analysis (via Fourier transformations) to predict the quality (strength) of bone repair.

PEMF effects in reducing stress-relief osteoporosis in plated dog radii also are being studied, along with their ability to affect longitudinal growth rates in epiphyses and apophyses. Furthermore, this phase of the project is focussing on the potential of induced pulsing currents to alter growth patterns in the immature spine and, thereby, to correct experimental scoliosis. Finally, one mechanism of PEMF action is being studied by following PEMF-induced changes in the calcium content of chondrocytes by isotype, transmission electron microscopy, and ion probe techniques.

[a]A program of the National Institute of Arthritis, Diabetes, and Digestive and Kidney Diseases, Westwood Building, Room 407, Bethesda, Maryland 20205.

### Study of Acceleration of Fracture Healing by Electrical Fields

**University of Pennsylvania**
**Medical Education Building**
**Philadelphia, Pennsylvania 19104**

**Carl T. Brighton, M.D., Ph. D.**

The object of this research is to continue investigating the effects of applied electrical fields on the acceleration of fracture healing in laboratory animals.

This project is designed to determine (i) the optimum parameters of applied (exogenous) electricity for accelerating fracture healing, (ii) the role of stress-generated (endogenous) electricity in fracture healing, and (iii) the mechanism of electrically induced osteogenesis at the cell level.

Methods used include the comparison of the osteogenic response of in vitro fetal rat tibia and in vivo healing rabbit fibula to constant direct current, to various pulsed unidirectional electric fields, and to various electromagnetic fields. Osteogenesis and bone healing are evaluated by incorporation of tritiated thymidine, $Ca^{45}$, and $^{35}SO_4$, as well as by maximum resistance to bending as determined by an Instron Testing Machine. The mechanism of action of electrically induced osteogenesis is sought by determining (i) $pO_2$ and pH changes in the vicinity of a cathode, (ii) changes in surface charge of cell membrane, (iii) mitochondrial release of calcium, (iv) cellular proliferation and migration, and (v) collagen and proteoglycan biosynthesis and processing.

### Study of Electrical Augmentation of Bone Formation and Ingrowth

**Battelle Memorial Institute**
**Columbus Laboratories**
**Columbus, Ohio 43201**

**Craig R. Hassler, Ph. D.**

The purpose of this research project is to continue the study of the basic phenomena of electrically augmented bone healing.

Previously, this study has shown that within reasonable limits of power dissipation, or current density, waveform or frequency seem to have little effect upon optimization of the augmentation phenomena. Experiments with anodized tantalum electrodes have shown that oxidation-reduction reactions occurring at the electrode surface are of little importance to the augmenting phenomena. The augmentation process seems to be effective throughout the healing period: no triggering phenomenon is observed.

Several areas require further research for understanding and correct utilization. The variables responsible for best stimulating bone growth are not known. The variability between animals is not understood: Why is it more effective in certain animals? The biochemical alterations which occur in vivo need to be understood and investigated in the in vivo situation. The comparison between electrode stimulation and electromagnetic coils needs to be performed within the same animal model so that a direct comparison between the two methods can be made. Further development of the promising phenomena of stimulating ingrowth into porous titanium and ceramic substrates needs to be continued.

This study employs a standard protocol and a previously developed animal model (the rabbit). Coils are produced and positioned to externally stimulate the same osteotomy system used for implanted electodes. Biochemical analysis involving hydroxyproline, proline cyclic AMP, cyclic GMP, and calcium levels is being continued. Electrochemistry of porous titanium surfaces is being assessed. The investigator is developing a mathematical model to assist in explaining the behavior of bone ingrowth into pores during electrical stimulation.

### Study of Investigations of Electrically Induced Osteogenesis

**Battelle Memorial Institute**
**Columbus Laboratories**
**Columbus, Ohio 43201**

**Craig R. Hassler, Ph. D.**

The purpose of this project is to test the hypothesis that electrically enhanced osteogenesis is the result of changes in ion fluxes, alterations in membrane lateral diffusion rates, or changes in cell potential acting at the cellular membrane.

The two modes of electrostimulation being studied are the use of internal direct-current electrodes and the application of external electric fields. During these modes, variations in ion flux, cell potential, and rates of membrane protein lateral diffusion can be determined. This investigator is studying the effects of these changes on the membrane-bound enzyme adenylate cyclase, an enzyme whose activity responds to electrical stimulation.

The project uses an in vitro cell model consisting of clonal cell lines with osteoblast-like activity derived from a rat osteogenic sarcoma. Direct measurements of physiologically important ion efflux and influx are made during stimulation. In addition, cell potential is determined with fluorescent cation cyanin dyes. Modulation of adenylate cyclase activity during electric stimulation or without stimulation is studied using a combination of ionophores, ions, and drugs to change cell potential and ion fluxes.

The information derived from this program will be used for a scientific comparison between the two modalities used clinically for enhancement of osteogenesis. In addition, information gained concerning the mechanism of electrically induced osteogenesis may be used eventually for improvement of the presently used clinical modalities or development of new methodologies for enhancement of osteogenesis and bone repair.

### A New Method to Measure the Rate of Fracture Healing

**Louisiana State University**
**Department of Orthopedics**
**Shreveport, Louisiana 71130**

**Subrata Saha, Ph. D.**

Radiographic examination is often inadequate for an exact evaluation of the state of union of a healing fracture and to detect early stages of osteoporosis. Therefore, there is a definite need for additional noninvasive means to measure the rate of fracture healing and to determine the mechanical integrity of bone in vivo. Ultrasonic and vibration tests have been attempted before as diagnostic tools to determine the degree of union of healing fractures. However, effects related to the soft tissue make such tests less reliable and therefore clinically less useful.

A noncontacting electromagnetic device has been developed which can detect the propagation of stress waves in a bone (produced by a piezoelectric

transducer or by a small impact) in a manner independent of the mechanical properties of the soft tissue. This device monitors the magnetic field produced by the piezoelectric charge associated with a stress wave propagating along a long bone. The stress waves in bone have also been monitored with the use of a vibrating traction pin placed in a magnetic field. Both of these methods have been used to record stress waves proximal and distal to the site of a partial fracture in excised human long bones. The study has found that transmission coefficients of the wave, the degree of simulated fracture healing, and microstructural variables such as porosity of the bone are correlated to a significant degree.

This investigator is conducting fracture healing experiments on dogs so that characteristics of the transmitted wave pulse can be calibrated to indicate the state of healing as evaluated by clinical observation, histological and X-ray examination, and mechanical testing. The sensitivity of the electromagnetic detector is also being improved so that it can be used easily to monitor the rate of fracture healing in patients. It is expected that development of such a method will result in improved health care of patients with fractured bones or other bone lesions. Such a method would also make it possible to detect osteoporosis at an early stage.

## ARTIFICIAL JOINTS

### Intermediate Organometallic Corrosion Products

**University of Pennsylvania**
**Philadelphia, Pennsylvania 19174**
**Johnathan Black, Ph. D.**

Metallic implants are used in large numbers in the practice of orthopedic surgery. All metals in use have finite corrosion rates. Possibly associated with release of metal by corrosion or other reactions, there have been a variety of clinical problems involving metabolic, immunologic, bacteriologic and carcinogenic responses. Research to elucidate the possible connections has been hampered by a lack of knowledge of the molecular form that the corrosion products take and the concentrations in which they are present in patients. In particular, it has been proposed that a variety of biologically active organometallic intermediate compounds exist as a result of corrosion in vivo.

The object of this research project is to detect, isolate, quantitate, and partially identify the bloodborne organometallic compounds that arise from the corrosion of the two most common orthopedic metallic alloy systems: stainless steel and cobalt-chromium.

These studies involve column fractionation of serum and treated tissue fragments, followed by atomic absorption spectroscopy. The studies have two important elements:

1. The use of a small animal/microsphere implant model to examine the effects of implant area/animal body weight ratio on the production of organometallic complexes and to predict the possible findings in patients.
2. The use of several longitudinal studies in patient populations to determine changes in blood levels of metallic and organometallic substances as sequelae to various orthopedic implant procedures.

### Contact Stress Distributions in the Hip and Knee

**University of Pittsburgh**
**Pittsburgh, Pennsylvania 15261**
**Thomas D. Brown, Ph. D.**

This study addresses the direct measurement of the contact stress distributions characteristic of the normal hip and knee. Since this important problem has not lent itself to conventional measurement techniques, only indirect estimates and simplified models are currently available.

Pilot work in this laboratory has shown that highly compliant miniature transducers incorporating piezoresistive elastomers are well suited for articular contact stress measurements. The signals from arrays of 20 such transducers, mounted in the articular cartilage of fresh autopsy specimens (40 hips and 40 knees), are processed by a computer and assembled into contour maps of the contact stress distributions. Cyclic (1 Hertz) loading of the joints to physiological levels is performed in an Instron unit.

The immediate results promise to be of significance in the areas of cartilage pathomechanics, prosthetic joint resurfacing, and stress analysis; the transducers themselves are potentially applicable to a wide range of current biomechanical measurement problems.

### Total Surgical Replacement of the Human Hip Joint

**Rush-Presbyterian-St. Luke's Medical Center**
**Chicago, Illinois 60612**
**Jorge O. Galante, M.D.**

This project is designed to study the fixation of prosthetic devices with porous materials and the wear characteristics of artificial joints.

The ability of a fiber metal composite to obtain bone ingrowth is being studied as it relates to: manufacture of the composite using titanium and cobalt chrome alloy; the long term biocompatibility and the problem of accumulation of metallic elements around the site of fixation and in distant organs; the possible carcinogenic effects of this material; and the application of this material to a model of total hip joint replacement, surface replacement and total knee replacement in experimental animals. Wear studies are being performed to investigate the characteristics and reliability of a wear-resistant titanium surface and the possibility of inducing changes and improvements in the wear characteristics of ultrahigh molecular weight (UHMW) polyethylene as a function of changes in its structure and physical properties.

### A Study of Friction and Wear of Prosthetic Bearing Materials

**University of California**
**Los Angeles, California 90024**
**Keith L. Markolf, Ph. D.**

A reliable method for laboratory testing of candidate materials for use in total joint replacement is essential to prevent the type of disasters that have occurred in the past when unproven materials have been introduced into patients.

The multichannel screening device and test protocol developed in the first two years of this project have been used to evaluate a variety of candidate materials with greater accuracy and reliability than has been previously possible. The test method used to date has involved adhesive-abrasive testing of materials in a flat-on-flat configuration, an analog of conforming-type total joints. A main objective of the project at this point is to expand the wear model to include round-on-flat testing as an an-

alog for certain low-conformity joints. Both wear models then will be employed to evaluate high priority candidate materials under conditions that accurately simulate the intended in vivo application.

Evaluation includes testing of new high-strength metal alloys (titanium 6-4, FHS cobalt chrome, Endocast cobalt chrome), ceramics (Alumina, Sialon, Macor) and polymeric materials (compression-molded ultrahigh molecular weight (UHMW) polyethylene, Poly II carbon fiber reinforced polyethylene and Delrin 150 polyacetal), with in-depth correlation of wear properties to critical test parameters. Emphasis is also being given to collaboration with other wear study groups in defining standard wear test criteria (ASTM, BSI, ISO).

### Study of Wear Particle Analysis in Human Artificial Joints

**University of Pittsburgh**
**Orthopedic Research Labs**
**Pittsburgh, Pennsylvania 15261**

**Dana C. Mears, Ph. D.**

As diarthrodial joints wear, they produce particles of wear. In this project the technique of ferrography has been adapted to the study of these wear particles, aiming to improve the early diagnosis of different arthritides and to provide a noninvasive, objective means for assessment and prognostication of natural joints and prosthetic joint replacements. Another goal of this project is to identify the wear modes operating in diarthrodial joints, and to contribute to the better understanding of joint rheology and tribology. To this end, the investigators are performing ferrographic analyses of saline joint washings provided by arthroscopic examinations of the knee. They are then comparing and integrating the ferrographic data with detailed medical histories of the patients.

The cellular responses to wear particles are being studied with cell cultures in vitro and with entire animals, thereby affording an insight into their role in the pathophysiology of arthritis. Particles are added to cultures of macrophages and synovial cells, and the conditioned medium assayed for extracellular proteases which degrade cartilage and for catabolic activity. Particles are then chemically and physically fractionated to determine which of their physical properties and chemical components contribute to which of the overall cellular responses. Particles, or certain of their components, are injected intra-articularly into rabbits. The animals are subsequently examined for possible arthritis changes, using radiographic, histological, cellular and biochemical criteria. Comparison of the data obtained from cells in culture with the results from animal studies permits assessment of the physiological relevance of the effects observed with the in vitro system.

### The Significance of Allergy to Orthopedic Implants

**University of California**
**Orthopaedic Research Lab**
**Davis, California 95616**

**Katherine Merritt, Ph. D.**

The aims of this interdisciplinary research program are to develop a better understanding of three aspects of allergic reactions to metallic orthopedic implants, and to demonstrate the effectiveness of an in vitro macrophage-inhibiting factor (MIF) test for patient screening and diagnosis of metal allergy. The three aspects being examined are: the influence of preexisting allergy on the outcome of the implantation, the consequence and prevalence of the development of allergy after implantation, and the importance of the metallurgical properties of implants on the development of allergic reactions.

A prospective study is being conducted to determine which patients are allergic to metals prior to insertion of a metallic implant, which acquire an allergy after implant surgery, and what effect the allergy has on the results of the surgery.

Patients admitted for metallic implant removal are also being studied to ascertain if there is a correlation between metal allergy and morbidity. An in vitro test for the production of leucocyte migration inhibition factor in response to metal salts is used to detect the allergic condition. The reliability of the MIF test is being determined in a study of patients with diagnosed metal contact dermatitis, and correlated with the results of a blast cell transformation test. The implants removed are examined for gross evidence of abrasion and corrosion and then for microporosity, casting voids, inclusions, and reactive grain boundaries, using standard metallographic methods. The results of the implant analysis are then compared to the results of the allergy test, to determine if the nature of the implant is an important feature in the development of allergy and of complications in these patients.

An animal study is also being conducted to more clearly define the time of development of metal allergy and its effect on the implant site. Rabbits receive stainless steel finger screws in the proximal humerus. One group serves as control, a second group is made allergic to nickel by injection prior to insertion of the screws, and the third group is made allergic by injection after the insertion of the screws.

### Mechanical Evaluation of Total Knee Arthroplasty

**Mayo Foundation**
**Rochester, Minnesota 55901**

**Richard B. Stauffer, M.D.**

This is a continuation of a biomechanical evaluation study of patients with disabling knee joint disease before and after total knee arthroplasty. The objectives of this phase of the study are: (i) to complete the number of patients previously proposed, and (ii) to perform objective analysis of the completed patient data to answer a series of specific clinical and biomechanical questions.

Previously 128 preoperative patients were studied, 41 of whom have returned for 1-year postoperative evaluations. Altogether, evaluation of 250 patients is being completed for different study periods because: (i) there has been a drastic change in the types of prostheses used in the last 2 years and the number of each type of prosthesis in the study must be kept at a significant level, and (ii) the clinical results have shown that the functional status of patients with total knee replacement is not stabilized at one year, so that followup study beyond that period must be conducted.

The project employs the goniometric method with computerized data collection and reduction capabilities. Based on a discriminative analysis technique, the eight most significant gait parameters have been used to establish a per-

formance index to grade the gait quality of total knee patients.

Two additional methods based on waveform analysis and phase relationship are being applied to differentiate refined gait variations. These results are presented on a graphic terminal, for visual inspection before hard copy is made as a permanent record. A gait evaluation summary has been developed to report to the surgeons the functional status of their patients.

### PMMA-Precoated Intramedullary Implants

**Clemson University**
**Clemson, South Carolina 29631**
**Andreas F. Von Recum, Ph. D.**

This is a feasibility study of intramedullary implants precoated with an acrylic bone cement. The femoral component of a hip prosthesis is precoated with polymethylmethacrylate (PMMA) and cured. Using the canine animal model, the prosthesis is implanted using the same PMMA and tested for 6, 12, and 24 months. The entire femur with implant is then removed and subjected to mechanical and morphological studies of the implant-bone interface.

This precoating method reduces the amount of PMMA used during the actual implanation procedure, and thus reduces some problems inherent to the use of PMMA, including increased temperature during polymerization which has adverse effects on tissues. The method also improves the transmission of load from implant to bone, improves intramedullary centering of the prosthesis, and increases interfacial shear strength over that of the same prosthesis implanted with conventional methods. The new method does not seem to induce any new risks, as no new materials are introduced into the body and no changes of the actual implantation procedure are proposed.

## LOCOMOTION

### Joint Contracture: Biomechanical-Chemical Correlates

**University Hospital**
**University of California San Diego**
**La Jolla, California 92103**
**Wayne H. Akeson, M.D.**

This project is a continuation of a study directed toward the elucidation of the joint contracture process in biochemical, bioengineering, and morphologic terms, and toward the development of therapeutic programs to minimize contracture formation.

Major changes in the composition of fibrous connective tissue have been demonstrated in experimental joint contractures as a result of immobilization. These changes were uniformly observed in ligaments, tendons, fascia, and capsular tissue of the knee joint. Significant correlations were shown between measures of strength of contracture and reduction in content of total hexosamine, water, and hyaluronic acid in the connective tissue matrix.

A working hypothesis has been constructed to explain these observations: that the loss of water and glycosaminoglycans in the periarticular connective tissue of immobilized joints contributes to changes in the physical characteristics of the affected joints. Presumably, this role is a permissive one, allowing a closer proximity of critical intercept points in the immobilized fibrous connective tissue mass which allows cross-links through one of two mechanisms: (i) random disposition of newly synthesized collagen or (ii) covalent cross-links between preexisting fibers. Significant increases of dihydroxlysinenorleucine (DHLNL), hydroxlysinenorleucine (HLNL), and histodinohydroxymerodesmosine (HHMD) in immobilized connective tissue have been demonstrated. Under this formulation, the fixed posture at the intercept points translates into restriction of motion in the joint composite.

In this next phase of the project, collagen turnover studies are being conducted using the Klein proline prelabeling technique to determine mass differences of new and old collagen in immobilized joints. This information is required to interpret the cross-link changes, as increases in reducible cross-links may simply reflect increased collagen synthesis.

The investigator is doing pilot projects to search for myofibroblasts in joint contracture tissue and to determine ratios of Type II to Type III collagen.

Therapeutic agents which hold promise in the prevention of contracture include penicillamine, estradiol, hydrocortisone, indomethacin (an inhibitor of prostaglandin) $CaNa_2$ EDTA. A pilot screening program is evaluating potential drug and hormone applicants for this purpose with in-depth evaluation of the most effective agents. It is possible to reduce the strength of contracture by penicillamine and by estradiol in pharmacological doses.

### New Hip Prosthesis and Fixation Modes (In Vivo Study)

**University of California**
**Center for Health Sciences**
**Los Angeles, California 90024**
**Harlan C. Amstutz, M.D.**

This project is designed to evaluate the feasibility of long term fixation of prosthetic joint components by means of bone ingrowth into porous surfaces without the use of acrylic bone cement. Three porous metal systems are being evaluated: sintered cobalt chromium beads, sintered titanium 6-4 beads, and sintered titanium 6-4 wire mesh (alloy of 90% titanium, 6% aluminum, 4% vanadium).

A canine hip surface replacement is used which was developed during the first 2 years of an ongoing 3-year project. Highly successful surgical procedures and histological techniques were developed and were used to evaluate numerous prosthetic fixation modes in 60 animals. With cement prostheses, cellular membranes invariably formed at the acrylic bone interface, a phenomenon associated with progressive loosening of the components. In contrast, the porous systems showed good bone ingrowth with no membrane formation in up to 6 months followup. The problems that were encountered were primarily related to the overall design of the components.

The investigator is now evaluating optimized design of both the femoral and acetabular components of the joint with the three porous metal systems in the canine model, with followups ranging from 1 month to 2 years. Analysis

includes combined techniques of microradiography, fluorochrome labeling, electron and light microscopy and specially developed histological procedures.

Loosening of cemented prosthetic joint components is currently the major cause of clinical failure. If the short-term promise shown by porous ingrowth fixation is fulfilled in this long-term project, application of these techniques to humans would be justified—to alleviate the rapidly growing number of clinical failures experienced with cemented joint replacements.

### Static Force and Stability Analysis of Human Elbow

**Mayo Foundation**
**Rochester, Minnesota 55901**
**Kai-Nan An, Ph. D.**

The objectives of this research project are to demonstrate a new technique in order to solve the indeterminate problem of static joint force analysis and to apply this technique to the study of the forces about the elbow joint, one of the most neglected joints in biomechanics research.

The components of the analysis consist of: (i) examining the electromyographic (EMG) activities and calculating the tensions of all the elbow muscles during various elbow functions; (ii) determining the forces on various articular surfaces of the elbow joint; and (iii) assessing the function of various ligamentous restraints in the elbow joint.

The methods of analyses include: (i) obtaining detailed three-dimensional information on the functional anatomy of all the elbow muscles and ligaments through cross-sectional dissection and biplanar X-ray investigations; (ii) developing three-dimensional mathematical models of the elbow for the calculation of muscle forces, joint contact, and ligamentous forces during elbow functions; (iii) performing in vitro ligamentous function tests by examining the load through the joint under sequential cuts of surrounding ligaments; and (iv) verifying the theoretical results by quantitative EMG analysis.

The results of this study are providing detailed three-dimensional force distribution data which have, up to now, been unavailable. These date have both far-reaching and immediate application to such pressing clinical problems as how the total elbow arthroplasty can be improved to decrease loosening, and what is required of the design to be in concert with the forces generated at the elbow. In addition, this information may help to explain the ever-increasing athletic injuries to the elbow, as well as provide a rational basis for surgery and rehabilitation.

### Biomechanical Study of Total Knee Replacement

**Rush-Presbyterian-St. Luke's Medical Center**
**Chicago, Illinois 60612**
**Thomas P. Andriacchi, Ph. D.**

The objective of this investigation is to obtain an improved understanding of the underlying biomechanics associated with total knee replacement design. The methodology is divided into three areas: experimental observation of net knee joint kinematics and kinetics; analytical determination of internal force distributions at the knee; and stress analysis of implanted prosthetic components. These three areas of study are integrated as follows: data generated on net joint reactions are used as input to a model for internal force calculations; internal force distributions are then input to the stress analysis models.

The basic questions addressed in this study include the following: (i) the relationship between patient variables and prosthetic design criteria; (ii) the extent to which patient knee mechanics varies among groups treated with different knee replacements designs and normals; (iii) the minimum mechanical requirements for an interface free from potential loosening.

Findings resulting from this study should aid in improved usage and design of total knee replacements.

### Locomotion: Idling Metabolism and Gait Dynamics

**Oral Roberts University**
**Tulsa, Oklahoma 74171**
**Robert B. Armstrong, Ph. D.**

**Harvard University**
**Cambridge, Massachusetts 02138**
**Richard C. Taylor, Ph. D.**

This project has two main objectives:

1. To determine the manner in which muscles and populations of fibers within muscles are recruited during locomotion: (i) as animals increase speed and change gaits; and (ii) as animals use their muscles for different tasks, i.e., positive mechanical work and elastic storage of energy.

2. To investigate the contribution of skeletal muscle to total resting metabolism.

The following techniques are used: electromyography (EMG) synchronized with high-speed movies to determine the activity and length changes of active muscles; glycogen depletion to determine the cross-sectional area of active muscles, populations of active fibers, and the power of active muscles; measurement of the length changes of tendons (using high-speed movies) as a means of determining force exerted by muscles during locomotion; and evaluation of blood flow to muscle groups together with oxygen extraction from the blood to measure oxygen consumption of muscles.

### Processes Underlying Arm Trajectory Formation

**Massachusetts Institute of Technology**
**Cambridge, Massachusetts 02139**
**Emilio Bizzi, M.D.**

This is a study of human motor control through measurement of free arm movements.

A commercially available movement monitoring system, the Selspot System produced by Selcom Corporation, provides for the first time the capability for fast accurate measurements of free arm movements. The advantage of accurate measurements is the richness of the set of trajectories that can be measured, revealing corresponding insights into motor control issues such as joint coordination, space-time tradeoffs in movement computation, and adaptation of learned movements to new situations.

The context for the experimentation has been developed from adapting theories of mechanical manipulator control to biological arm control. The notion of an incomplete tabular representation of movement parameters (i.e., sparse lookup tables) is put forth to solve the problems of intractable equations of motion and of mechanical modeling inaccuracies. The implication of a sparse

lookup table, namely that a relatively small number of movements can be executed accurately, has led the investigators to test experimentally (i) for human arm movements that are executed less accurately than others, and (ii) how a sparse lookup table can be used to generate more complex arm trajectories. Experiments with monkeys are revealing the extent to which feedback is required for proper execution of these strategies.

### Influence of Wrist Pathomechanics on Hand Function

**University of Iowa**
**Iowa City, Iowa 52242**
**William Blair, M.D., M.A.**

The objectives of this project are:

1. To continue basic biomechanical investigations to further improve understanding of normal and pathomechanical states of the rheumatoid wrist and its influence on hand function.
2. To develop reliable methods for the evaluation of patients with abnormal states of the wrist by using existing technology to quantitate the kinematic behavior of the wrist joint.
3. To evolve better methods of treating deformed wrists by providing the basic biomechanical information about their motions and forces needed to intelligently evaluate and prescribe surgical options, define requirements for potential prostheses, and determine optimal treatment modalities.

Methods are clinical and experimental; patients and cadaver specimens are used.

Clinical studies are emphasizing anatomical and surgical findings relating to carpal and wrist joint ligaments and correlating these findings with the experimental studies.

Experimental studies are largely concerned with developing and analyzing simulated rheumatoid wrist joint deformities in the cadaver and with developing optimum mechanical design criteria for a total wrist prosthesis.

This project should produce information of sufficient reliability for proper planning of the clinical and rehabilitative care of patients with wrist deformities.

### Biomechanics of Hip and Knee

**University of Iowa Hospital**
**Iowa City, Iowa 52242**
**Richard A. Brand, M.D.**

This project is the continuation of a study of the biomechanical environment of the hip. The major objective of the original grant was to improve the surgical treatment of patients with arthritic hips by estimating the three-dimensional loading on the hip and then identifying ways, through surgical geometry and implant design, to reduce loading.

A sophisticated, reliable method to estimate the three-dimensional loading of the hip during gait and activities of daily living has been developed. The method involves the use of biplanar photography to record body segment displacement histories. Foot-floor reactions are measured with a force plate. Body segment inertial properties are determined from anthropometric measurements. The kinematic, kinetic, and inertial property data are combined in a Newtonian model to predict the intersegmental resultant forces and moments. The resultant forces and moments are then "distributed" to the muscles and articular surfaces of the hip using a linear optimization scheme. This method has been applied to study loading in the human hip and to identify ways to decrease loads and stresses with treatment.

This project is also a continuation of studies of the hip, extending them to the knee joint. A refined three-dimensional model of the lower-extremity muscle and ligament anatomy is being developed which is being followed by an investigation of new schemes to distribute the resultant hip and knee forces and moments to the muscles and ligaments. Validation procedures on the various distribution schemes are carried out for normal and pathologic gaits and other activities of daily living. Those schemes which are most appropriate are used to collect data on the mechanical function of normal and diseased hips and knees. These data are being analyzed in forms useful for designing treatment modalities.

### Study of In Vivo Loading on Total Knee Replacement

**Case Western Reserve University**
**Orthopaedic Engineering Laboratory**
**Cleveland, Ohio 44106**
**Richard H. Brown, Ph. D.**

The purpose of this project is to determine the in vivo loading data from total knee joint replacements. These new joint replacements have enough telemetry circuitry incorporated within the body of the tibial components to provide seven channels of loading data. These are being used to record the loads on the device, allowing for the determination of the three forces and the three moments on the tibial components.

### Three-Dimensional Analysis of Knee Motion

**Case Western Reserve University**
**Glennon Engineering Building**
**Cleveland, Ohio 44106**
**Richard H. Brown, Ph. D.**

The purpose of this project is to determine the kinematics of adult knee joints and postarthroplasty joint replacements using a system of three-dimensional radiographic analysis of in vivo bony structures. Implanted markers are utilized to determine the kinematics of both normal and pre-arthroplasty deranged knees. The normative data are for adults of both sexes and varying ages. The resultant postarthroplasty kinematics of constrained, semiconstrained, and totally constrained prosthetic types are being determined. The sensitivity of this analysis technique to detect joint loosening is evaluated also.

### Pressure Distribution Under the Foot

**Pennsylvania State University**
**University Park, Pennsylvania 16802**
**Peter R. Cavanagh, Ph. D.**

This project involves a novel clinical technique for the measurement of the pressure distribution beneath the normal and abnormal foot during locomotion. This technique provides the orthopedist or physiatrist, for the first time, both a quantitative measurement and a graphic representation of the tem-

poral and spatial variations of the stresses generated on the plantar surface of the foot. Preliminary work with a related technique, impractical for clinical applications, has demonstrated the feasibility and potential of this approach.

The first phase of this study involves development of a measurement system consisting of flexible piezoelectric transducer arrays of varying geometries and a common supporting data acquisition and graphic display package. In the second phase, a study will be made of the variabilities in the pressure distributions within and between normal subjects walking and running over a range of speeds. Techniques will also be developed for presenting these data in a form that shows both the mean stresses and their variations as functions of time and position.

Finally, in the third phase, the device will be applied to the study of several well-defined groups of patients exhibiting a variety of lower-extremity pathologies. The aims of this phase are: (i) to determine the pressure distributions characteristic of each pathology and the way in which these deviate from the norms established in the second phase; (ii) to investigate computer-aided diagnosis of these pathologies using pattern-recognition techniques; (iii) to explore the use of the technique in the prescription and evaluation of orthotic devices; and (iv) to provide a reference data base for use of the technique in clinical practice.

### Functional Forces in Normal and Abnormal Fingers

**Mayo Foundation**
**Rochester, Minnesota 55001**
**Edmund Y. Chao, Ph. D.**

This is the continuation of an analysis of normal finger force performed by the technique of optimization. A graphical method has been used to present the results for a better understanding of the redundant force analysis problem. Normative models for the fingers were developed to perform simulation studies of abnormal hand conditions. Accurate instruments were fabricated and tested for patient evaluation. Important data have been produced.

The present extension of the project attempts to: (i) expand the study to analyze normal and abnormal thumb forces, (ii) determine capsuloligamentous forces of the joint, (iii) analyze the pathomechanics of finger and thumb deformity by simulation studies, (iv) perform objective patient evaluation, and (v) obtain qualitative validation of the analytical results based on quantitative electromyography (EMG) analysis.

A normative thumb model is being developed following the same technique, optimization, as was applied to the fingers. When the muscle strength is reduced due to pathological conditions, the functional forces are calculated in a reverse manner by treating the external applied force as an additional unknown.

Detailed cross-sectional studies are performed to construct the capsuloligamentous model, and its force components are determined by equipollent force analysis technique. Cadaver finger specimens are tested under bending and torsion to assess the role of the ligaments and capsule in maintaining joint stability. Patients with pathological conditions are evaluated biomechanically; integrated EMG's of extrinsic and intrinsic muscles are measured while the hand is performing isometric functions. These values are being correlated with theoretically predicted forces for qualitative comparison.

### Medial Gastrocnemius Muscle Function in Locomotion

**Emory University**
**Anatomy Department**
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**Arthur W. English, Ph. D.**

Traditionally, considerations of the roles played by the medial gastrocnemius (MG) muscle during stepping have been limited to extension of the ankle joint, either as an active force during the late swing phase or as an elastic body during the stance phase. The main objective of this study is to consider the ankle extensor function of MG in more detail than reported previously and to consider possible roles for MG other than simple talocrural extension.

Normal locomotor function is examined in the cat using a combination of biplanar high-speed cinematography, force platform analysis, and multichannel electromyography. Limb movements (joint angle changes and body segment motions) and activity patterns in MG and all of its possible synergists are studied before and after partial and total denervation of MG. Analysis of this kinetic and kinematic data permits an accurate correlation of biomechanical events of abnormal step cycle and the roles of MG as elaborated by the central nervous system.

Results of preliminary pilot studies indicate that MG functions (i) to produce acceleration of the talocrural joint during the swing phase of stepping so that the foot is moved with a large average velocity, (ii) to decelerate extension of the knee joint just prior to foot placement, (iii) to stabilize the talocrural and subtalar joints during the early stance phase, and (iv) to extend the foot and provide forward thrust via an elastic stretch-shorten mechanism during the stance phase.

The applicability of studies of both peripheral and central aspects of the locomotor system in cats to humans has a long and well-established history. This project should contribute information as to the roles played by individual synergistic muscles during stepping, provide valuable peripheral correlates of the central program for stepping, and provide information on normal muscle function which can be used by specialists in rehabilitation medicine and other fields.

### In Vivo Loading in Total Hip Joint Replacements

**Case Western Reserve University**
**University Hospitals**
**Cleveland, Ohio 44106**
**Kingsbury G. Heiple, M.D.**

The purpose of this project is to determine the in vivo loading data from total hip joint replacements. These hip joint replacements have incorporated within the neck of the femoral component all the circuitry required to provide, by telemetry, three channels of loading data. One channel is used to record the axial load on the neck, the other two to record the bending moments about two orthogonal axes normal to the neck axis.

## Development of a Clinically Applicable Model of Gait

**Children's Hospital Medical Center**
**Boston, Massachusetts 02115**
**Joseph M. Mansour, Ph. D.**

This project is developing a biomechanical model of human gait. The model is constructed as a multilinked open chain system whose motions are governed by the principles of dynamics and kinematics in conjunction with known elements of the physiology and functional anatomy of gait. The model is employed for the analysis of both normal and pathological gait. Using this model the relative influence of both active muscular contraction and passive tissue constraints on motion is evaluated.

For pathological gaits, the investigator is evaluating the response to a treatment modality by analytically describing the mechanical response to treatment and comparing this to the actual patient response observed in the gait laboratory. In this way the effects of treatment and the mechanical compensatory mechanisms that arise secondary to the treatment may be evaluated.

## Ballistic Walking: Normal and Pathological Gaits

**Harvard University**
**Cambridge, Massachusetts 02138**
**Thomas A. McMahon, Ph. D.**

These theoretical and experimental studies are devoted to the question of whether or not a model of human gait is realistic in which the muscles of the swing leg are silent after the end of the double support phase.

The studies examine both normal and pathological gaits at both fast and slow speeds. Pathological gaits addressed include Trendelenburg, gluteus maximus, ankylosis of the knee, instability of the knee, equinus, spastic plantar flexion of the ankle, and dropfoot in paralysis or muscular weakness. The predictions of the model, to be tested against new and existing experimental and clinical observations, will allow a simple criterion to be established within each gait pathology, marking the boundary between mild and severe handicaps to progression.

## Kinematic Studies of Normal and Abnormal Locomotion

**Medical College of Wisconsin**
**Veterans Administration Center**
**Kinesiology Research Lab**
**Wood, Wisconsin 53193**
**M. Patricia Murray, Ph. D.**

This project is a continuation of kinematic studies of multiple simultaneous displacement patterns of walking in patients with specific arthritic and neurological disabilities, comparing their disordered walking performance with standards of normal variability which have been established previously. The project is also measuring the nature and amount of assistance required for walking, utilizing force-recording canes and crutches.

Methods have been developed to obtain quantitative measurements of basic mechanisms which are operative in causing gait abnormalities. These mechanisms include muscle weakness, muscle rigidity and spasticity, joint immobility, and postural unsteadiness and upright instability. Ranges of normal variability for these mechanisms have been established which serve as baselines for comparing deficits in disabled patients.

Using a multifaceted approach, the investigator is studying patients with severe arthritis before and after various types of major reconstructive surgery. She is comparing the effect of different types of total hip and knee arthroplasties on various components of function such as walking performance, cane force, muscle strength, joint mobility, and weight-supporting activity.

This project also continues studies of the interrelationship between: (i) muscle spasticity, rigidity, or weakness; (ii) postural steadiness and upright stability; and (iii) walking performance in patients with Parkinson's disease and hemiparesis following stroke. Measurements are being made of the effects of various drugs on reducing spasticity, and of various braces on improving walking performance.

## Influence of Skeletal Implant Materials on Infection

**University of Florida**
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**Gainesville, Florida 32610**
**Roy W. Petty, M.D.**

The incidence of infection after skeletal implant surgery is low, but the disastrous results make postimplant infection a major complication. In vitro experiments have suggested that some implant materials adversely affect immune mechanisms against infection. The clinical significance of in vitro impairment of immune mechanisms is not known, but can be determined in an in vivo experimental model.

In this project, an implant of polymethylmethacrylate (PMMA), high density polyethylene, stainless steel, or chrome-cobalt alloy is placed in the surgically prepared femoral canal of a dog following the instillation of low dose diluations of bacteria. Occurrence of infection is determined by wound evaluation and bacterial culture; incidence of infection is expressed as the infectious dose-50 (ID-50). Incidence of infection with the various implant materials is being compared.

It is expected that, in the presence of bacteria, all implant materials, as compared to no implant, enhance the development of infection. The purpose of the project is to determine if the bone cement PMMA enhances infection development more than the other commonly used implant materials, and to determine if any commonly used implant materials enhance development of infection to a greater extent than the others.

Further experiments are determining the efficacy of various treatment methods in increasing the ID-50 (that is, in decreasing the incidence of infection) in musculoskeletal wounds in which implants are used. Systemic antibiotics, irrigation of wounds with antimicrobial solutions, and use of PMMA containing antibiotics are being evaluated.

The results of these experiments will have direct clinical application by determining the most effective means of preventing infection when bacteria contaminate wounds in which musculoskeletal implants are used.

### Studies of Synovial Joints

**University of Florida**
**Gainesville, Florida 32611**
**George Piotrowski, Ph. D.**

The objectives of this project are: to develop a general instrumentation system for the measurement of joint forces, motions, and intra-articular pressures of living synovial joints; to verify the precision and accuracy of these measurements; and to study the functioning of living synovial joints using this instrumentation. Data obtained are being correlated to various theories of joint lubrication in order to determine the role of various joint constituents, particularly synovial fluid and cartilage, in the functioning of synovial joints.

### Diagnosis of Loose or Damaged Total Joint Replacement

**Hospital for Special Surgery**
**New York, N.Y. 10021**
**Timothy M. Wright, Ph. D.**

Because of the increasing use of total joint replacements and the need to correctly diagnose mechanical degradation of such implants, the goal of this project is to develop a technique of in vivo joint monitoring by means of acoustic emission.

To accomplish this goal, the acoustic emission signatures of implant metals, the bone cement polymethylmethacrylate (PMMA), and bone are being developed under appropriate loading conditions. Composite in vitro structures consisting of cadaver bone, PMMA, and appropriate implanted total joint replacements are monitored for their acoustic emissions while subjected to heavy static and cyclic loads. A two-microphone technique is used, so that the locations of the emission sources may be detected in two-dimensional space. A finite element analysis is provided, using appropriate material properties and geometries, so that correlations between predicted high-stress areas and regions of acoustic emissions may be performed.

When sufficient accuracy and repeatability has been achieved in the in vitro studies, an in vivo program will be initiated using the identical available equipment. Patients at high risk for mechanical degradation of implants on clinical variables such as weight, bone size, and level of activity will be monitored, and correlations between continued clinical findings and acoustic emission findings will be performed.

## EXERCISE PATHOPHYSIOLOGY

### Disuse and Exercise in Conditions of Muscular Atrophy

**University of Texas**
**Health Science Center**
**Houston, Texas 77025**
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The primary objective of this research is to better delineate the nature of the molecular events which cause the early decline in the rate of protein synthesis in skeletal muscle after hindlimbs of rats are immobilized with plaster casts. Answers to the following related questions are being sought: (i) Do increased glucocorticoid levels play a role in inhibiting protein synthesis? (ii) Does the development of insulin resistance by the muscle cause a decline in protein synthesis activity? (iii) Is the decline in protein synthesis related to a decreased ability of the cell-free ribosomal preparation to synthesize polypeptide chains? and, (iv) Do calcium pool levels change in such a manner as to contribute to a decline in protein synthesis?

The second major objective is to determine whether insulin resistance plays a role in the atrophy of skeletal muscles. Muscular atrophy and insulin resistance occur in diabetes and obesity, as well as in other diseases such as cancer, cystic fibrosis, acromegaly, Cushing's syndrome, and myotonic dystrophy. Using normal animals as a control, this study is determining whether protein synthesis activity is less for a given dosage of insulin during the in vitro incubation of skeletal muscles from diabetic-obese animals. These findings will then be related to the glucose uptake per insulin concentration and to the insulin binding characteristics in skeletal muscles.

Physical exercise is known to improve glucose tolerance and to decrease insulin requirements in diabetic humans. In this study, diabetic-obese animals are exercised. Subsequently, data will be compiled to determine whether glucose uptake by skeletal muscle increases per dosage of insulin, and whether the affinity of insulin receptors in muscle increases after a single bout of exercise.

### Alterations in Skeletal Muscle with Use and Disuse

**Marquette University**
**Department of Biology**
**Milwaukee, Wisconsin 53233**
**Robert W. Fitts, Ph. D.**

It is well established that the motor activity pattern regulates physiological and molecular processes in skeletal muscle. The objective of this study is to perform the first comprehensive and integrated analysis of the adaptive responses that occur with muscle use and disuse in all three mammalian skeletal muscle fiber types.

Wistar female rats have been divided into groups to characterize the effects of (i) hindlimb immobilization produced by casting, (ii) chronic electrical stimulation of hindlimb muscles, and (iii) exercise-training. A novel approach is being used in a separate series of experiments to assess the effects of chronic electrical stimulation (i.e. motor activity) on rat hindlimb muscles during and following immobilization. The effects of exercise-training (treadmill running) on muscle recovery from immobilization is also being studied.

At selected time periods after the initiation of the above experiments, muscle function is evaluated by studying the isometric and isotonic contractile properties of selected muscles representative of the three mammalian fiber types. Biochemical studies are also performed on myosin and the sarcoplasmic reticulum (SR). Myosin and the SR are extracted from Type I, IIA, and IIB muscle samples. The myosin light and heavy chains are analyzed using polyacrylamide gel electrophoresis; functional studies are conducted on myosin ATPase. The SR is evaluated to determine $Ca^{++}$ uptake, binding kinetics, and the ATPase activity of this membrane system. Fiber type differences in the myosin and SR structure and function are evaluated, the effect of use and disuse determined, and the results correlated with the physiological findings.

## Adaptation of Muscle to High Intensity Exercise

**University of Texas Health Science Center**
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**William J. Gonyea, Ph. D.**

The objectives of this research project are to further define the process whereby skeletal muscle adapts to high-intensity (weight-lifting) exercise and to elucidate the mechanisms which control this process.

In this project, adult cats are operantly conditioned to flex their right wrist against increasing resistance to receive a food reward. This procedure has the advantage of inducing significant hypertrophy in the muscles of one limb, while the muscles of the opposite limb can be used for comparative studies. This exercise regimen has been shown to increase the number of fibers in the muscles of the exercised limb. The mechanism for this increase has been shown to be fiber splitting.

In this study, the structural and histochemical features of muscle fibers that are undergoing division by splitting are characterized, and the adaptive changes that occur in the exercising muscle that contribute to fiber splitting are investigated. Alterations in the contractile properties of the exercised muscle are explored, and pharmacological blocking drugs (d-tubocurarine and decamethonium) are used to evaluate the component parts of mixed muscles. Electromyography (EMG) is used to assess adaptive changes in the function and recruitment of exercising muscles.

This study will further elucidate the dramatic structural and functional alterations that occur in skeletal muscle that is adapting to high-intensity exercise, and will define the mechanisms that control these adaptive processes.

# NATIONAL SCIENCE FOUNDATION
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# SCIENCE AND TECHNOLOGY TO AID THE HANDICAPPED

James C. Aller, Sc. D., Program Manager

## Microprocessor-Based Integration of Artificial Reflexes and Sensory Feedback for Prosthetic Control

**Scientific Systems, Inc.**
**54 Rindge Avenue Extension**
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**Wolfram Jarisch, Biomedical Engineer**

This is a final project report, award number PFR-80-09412, based on work supported by the Small Business Innovation Research Program from 9/1/80 to 2/28/81.

This project seeks to improve the performance and usefulness of a microprocessor-based prosthetic arm so that the requirements for continuous visual supervision of prosthetic movements are lowered.

Artificial reflexes and sensory feedback in a prosthetic device have been recognized as important factors for improving prosthetic performance. Associated with the loss of a limb a variety of reflexes and senses are lost. If these are to be substituted, the question arises which are most relevant for a given lost limb function, and for a particular individual.

By way of a literature review of psychometric measurements and current neurophysiological models, the nature of the problem is identified as an optimization problem. In the particular setting the problem presents itself as a stochastic problem in a high dimensional parameter space. Conventional experiment designs and regression techniques are inadequate to acquire the information necessary for optimization with a reasonable experimental effort for a given individual.

In order to cope with these difficulties, a novel stochastic optimization algorithm is developed based on hybridization of ideas from stochastic function minimization, conjugate gradient methods (orthogonal projections), and other statistical concepts. The concept of "high dimensionality" is developed and is cast into a probabilistic framework.

The algorithms can be utilized to construct on-line, for a particular amputee, the necessary artificial reflex laws and sensory feedback codes. These laws and codes may then be placed in a microprocessor controlling the prosthetic device.

## Use of Voice-to-Text Conversion in Deaf-Hearing Dialogues

**SRI International**
**Telecommunications Science Center**
**Computer Science and Technology Division**
**Menlo Park, California 94025**
**Earl Craighill, Ph. D.**

This is the first year of a 3-year continuing award, proposal number ECS 80-23527, fiscal year 1981.

This research explores methods of coupling voice-to-text (VTT) conversion technology with speech synthesis devices to allow better communication between the deaf and the hearing.

The research specifies, demonstrates, and evaluates VTT systems that are practicable and useful in dialogues between a hearing person talking over a phone to a deaf person who is typing.

Specific tasks are to: (i) Define the necessary system parameters of a usable VTT system, including the level of recognition performed by machine, the degree of accuracy of machine operation, and the amount of training required by deaf and hearing persons; (ii) Demonstrate an operational system coupled to the phone network; (iii) Determine the extent to which deaf users can provide their own syntactic and semantic analyses; and (iv) Identify key research problems that require solution.

Experiments are conducted to simulate communication between deaf and hearing persons and include simple information-transfer tasks as well as fully interactive representative dialogs.