VI. Biomechanics

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VI. Biomechanics

A. Joint Studies

1. General

Biomechanical Studies of Bones and Joints

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Purpose—This project was a pilot study to collect data for further study of the biomechanics of bones and joints. Specifically, this study investigated the instantaneous changes in the dynamic or vibration response of knee joints. It appears that in traumatic injury or degenerative joint disease the dynamic response of the knee is different from that of damaged knees.

Progress—This study developed specialized instrumentation to measure the dynamic response. The instrumentation consists of an accelerometer to measure discontinuities in the movement of the joint and an acoustic emission pick-up to measure the resonance of the bone. Preliminary data indicated that the accelerometer readings were adversely affected by the soft tissue around the bone.

The Antagonist Muscle and Its Role in Maintaining Joint Stability

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Sponsor: LSU Bioengineering Foundation

Progress—The previous phase of this study clearly indicated that the elbow antagonist muscle is active at various levels during isometric contraction. The current phase quantified the activity level and showed that the antagonist activity regulates the torque about the joint in such a manner that it compensates for the effect of the gravity vector, force level of the agonist, joint angle, and variations in the lever arm formed by the muscle tendon insertion in the bone. The net effect of the antagonist activity is to maintain joint stability, regulating the torque about the joint in the face of external and internal disturbances.

A significant new finding shows that mechanoreceptors are found in the ligaments, and upon ligament deformation they activate the antagonist muscle in a fast and direct reflex arc so that joint ligament overloading causes increased activity in the antagonist to assist in negotiating with the overload.
2. Lower Limb

Pathokinesiology of Anterior-Cruciate-Ligament Deficiency

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Purpose—The objective of this project was to investigate the deviations from normal kinematics and muscle function in knees with ruptured anterior cruciate ligaments. Measurements were made using six-degree-of-freedom goniometry and electromyography during walking and pivoting.

Progress—The knee kinematics of eight individuals with uninjured knees and of seven individuals with injured knees were investigated. The kinematics were quantitated using helical motion analysis. The results of the helical motion analysis revealed clearly that the knee is definitely neither a hinge nor a planar joint. It is a dynamic joint whose kinematic behavior changes over the stride. A stationary joint center has been assumed in many biomechanical models and the mechanics are sensitive to its location. Thus, more sophisticated models are necessary for more than a general approximation to knee joint function.

The results also quantitatively define the changes in kinematics that occur from the loss of the anterior cruciate ligament. These changes are significant. Ligamentous loss results in more adduction and external rotation during certain periods of the stride. Also, the range of translation of the tibia in the medial/lateral direction is reduced and its mean translation is more medial.

The study of EMG patterns in muscles acting around the knee joint reveals that individuals with injured knees have deviations in EMG linear envelopes with respect to the normal population. The most significant difference during walking is that the rectus femoris no longer has peak activity during the swing-to-stance transition period. During pivoting the most significant difference is that in the gastrocnemius the amplitudes of the major and minor phases of activity are switched. Unusual phasing of the peak activity in certain muscles is consistent throughout the patient population. Increased activity of otherwise quiescent muscles during specific intervals of the gait cycle can most likely be related to the absence of the anterior cruciate ligament and the support it would normally afford.

Future Plans—It is planned to continue this study in order to increase the size of the database. With a sufficiently large database, the effects that corrective procedures and joint prostheses have on knee kinematics and muscle function will be studied.

Development of Diagnostic and Therapeutic Procedure for Anterior-Cruciate-Ligament-Deficient Knees

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Progress—A procedure was developed in which electromyograms (EMGs) of the quadriceps and hamstrings were collected during knee extension at maximal effort on the Cybex II system.
at quasi-isometric speeds of 10 degrees per second.

It was shown that patients with anterior-cruciate-ligament-deficient knees underwent full or partial torque failure about 37 to 46 degrees of knee flexion angle with simultaneous EMG reduction from the quadriceps and EMG increase from the hamstrings.

Patients with substantial muscle exercise therapy post-injury did not demonstrate failure, although EMG patterns were similar.

The evaluation system is undergoing modification for permanent installation in the Sport and Knee Clinic for routine use.

**Computer Simulation of Knee Joint Mechanics**

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**Purpose**—Computer models of human motion (e.g., gait, jumping, cycling, etc.) require not only models of muscle and musculoskeletal geometry, but also models of the joints. Current joint models that accurately reflect knee behavior are highly complex, making them unsuitable for real-time whole-body dynamic simulations of motion, because the knee modeling task itself generally requires excessive computation.

The goals of this study are to determine the principal flexor/extensor mechanisms of the knee and to develop a computationally efficient knee joint model that can be incorporated in our overall dynamic system model of the lower extremity. Our efforts to develop and use such a model include the investigation of real-time computer animation as a clinical research tool. We envision realistic animation as such to be an informative and easily interpreted display of calculated results.

Real-time capability extends the usefulness of this display even further, because the effect of adjusting model parameters is evident immediately. For example, such a model may be used to explore the feasibility of lower-limb functional electrical stimulation (FES) systems on a patient-by-patient basis before surgery is actually performed.

Development of lower extremity musculoskeletal computer models of mammalian movement requires understanding of joint mechanics. In typical simulations of human gait, posture, and jumping, the knee joint is treated as a simple, two-dimensional pin joint. Yet it has long been known that the knee acts in a much more complicated fashion. For example, numerous reports describe the contributions of articular surface geometry, movement of the instantaneous axis of tibial-femoral joint rotation, patellar mechanics, and so on. Highly detailed computational models have therefore been developed that take some of these factors into account, enabling researchers to predict joint behavior given a specific set of conditions. Although some other joints behave similarly to pin joints, these and other findings indicate that the knee does not and that it should be described more accurately due to its major influence on human mobility.

**Progress**—Thus far, with our musculotendon model, we have used combinations of simple mechanical elements (springs, dashpots, etc.) to form a system that behaves approximately like that of the living tissue. Such a model is needed for the knee joint as well, in order to reflect the effects of joint geometry and the mechanical leveraging action of the patella, and to determine the relative influence of various other joint phenomena on whole-body motions.

A minimal set of elements composed of idealized strings, rods, and cams is used to model the ligaments and tendons, the patella, and the articular surfaces of the femur and tibia, respectively. A two-dimensional model is formulated to allow independent specification of contact surface geometry, location, and movement of the instant center of joint rotation as a function of knee flexion angle, patellar and patellar ligament lengths, and initial orienta-
tions. Geometric and motion constraints are imposed to prohibit unrealistic configurations and motions, such as a tendon passing through the surface of the bone. Using this model with these constraints will enable us to emulate published experimental data and thus to determine, in essence, the mechanical operations of the joint.

Implementation of the model on a digital computer is nearly complete. Ongoing efforts are concentrating on determining realistic joint specifications and input parameters.

Future Plans—Future plans are to expand the joint model in order to explore the influence of patellar geometry and the effects of tendon and ligament elasticity, friction, and external forces. Once a working model is developed, we will incorporate it into our model of the lower extremity. We then intend to animate our real-time computer simulations of motion in order to evaluate limb control and coordination schemes, prostheses, and external supporting structures specific to FES patients.

Comprehensive, Quantitative, Predictive Model of the Human Knee Joint

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Purpose—The knee is the largest, most complex, and most frequently injured of the synovial joints in the human body. The knee is subject to high complex loading, especially in single leg support, in athletics and in unexpected falls, and is susceptible to externally induced trauma due to the absence of thick, soft surrounding tissue. Knee injuries frequently culminate in permanent debilitation and may lead to osteoarthritis and the need for consequent replacement by artificially implanted joints. Prevention and treatment of injuries could be improved by better knowledge of the kinematics and dynamics of the normal and pathological knee, by better defining the contributions of the passive constraints—the cartilage surfaces, menisci, and ligaments—and by better understanding of the roles of the active constraints—the 15 muscles that act across the knee joint, 12 of which are biarticular with either the hip or the ankle.

This project is developing a comprehensive, mathematically expressed, computer-manipulable model of the human knee joint with which to calculate the kinematics and dynamics of the normal knee. Then, following adequate verification, we will employ the model to simulate the consequence of specific losses observed in the pathological knee. This model is expected to contribute to a better understanding of preventive and treatment modalities.

The end-stage treatment of total replacement prostheses is yet to be as successful and widely adopted as those of the total hip replacement prosthesis. The understanding of the normal and pathological knee derived from the model is also expected to contribute to the specifications for improved total knee replacement prosthesis.

Progress—The mathematical model will be verified in part by comparison with unique in vivo data on the kinematics of the human knee joint acquired using the MIT TRACK movement analysis system. During acute experiments, the TRACK light-emitting-diode arrays were mounted on bone pins inserted into the femur and tibia bones of a consenting volunteer. Preliminary reduction of the data disclosed distinctly different patterns of motion in the loaded and unloaded joints. During the stance phase of gait, the motion appears dominated by the bony geometry and is definitely nonplanar. In voluntary flexion-extension of the unloaded knee, different trajectories occur in flexion versus extension, the articular surfaces do not appear to be in contact, and the motion is essentially planar. These data refute commonly accepted planar linkage models of the knee joint that characterize the role of the
anterior and posterior cruciate ligaments as a “four-bar linkage.”

More refined processing of this unique kinematic data set has included a bachelor’s thesis that evaluated different filtering and smoothing approaches, the adoption of Woltring’s quintic-spline-smoothing approach, and the adaptation of this scheme to a 32-bit computer with a large virtual memory so as not to require sectoring of the data set.

The geometric mapping of the knee articular surface geometries and that of the menisci will employ an ultrasonic technique developed earlier in the hip investigation. A new ultrasonics scanner that can operate in spherical, cylindrical, or Cartesian coordinates has been designed and fabricated in the laboratory.

The mechanical properties of the ligaments for the model must go beyond the extant literature, which is concerned primarily with failure testing. The dynamic properties of bone-ligament-bone specimens were examined over the load range of interests to determine force relaxation as functions of initial load, initial strain rate, and after cyclical activity at several physiological frequencies.

Techniques have been developed and applied for using the TRACK system to establish and record the geometry of ligament and muscle insertions and origins. Dissection and measurement of the first human lower extremities are under way. To provide an independent data file on the muscle and ligament origins and insertions, the same leg has already been scanned with both computer-tomographic and magnetic resonance imaging machines.

**Future Plans**—In the future, we will compare the geometry from the reconstructed scan data with the TRACK physical measurements to test the feasibility of a noninvasive method for establishing specific muscular skeletal data for incorporation in future knee models based on different cadaver extremities. This technique may also prove clinically useful in planning and executing orthopaedic procedures.

## B. Spine

**Trunk Analysis System**


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**Sponsor:** Liberty Mutual Insurance Company

**Purpose**—In 1984, we began to explore the possibility of using our median frequency technique, along with measurements of conduction velocity, to assess the performance and interaction of the muscles in the trunk. One goal of this research is to develop a reliable screening method for distinguishing between the performance of trunk muscles in individuals with or without back disorders. To ensure accurate assessment of back performance, many individual muscle groups must be monitored.

**Progress**—A special restraining device that reliably stabilizes the trunk was designed to assure that the muscle activity observed is actually associated with the flexion and extension torques being monitored. Considerable effort was made to design the restraint apparatus so that the individual’s pelvis could be immobilized for at least an hour without discomfort.

The device is constructed from a commercially available hexagonal tubing system used in many hospitals. This allows the apparatus to be tailored to a large variety of subjects and postures. Specially contoured adjustable front and rear restraining pads hold the subject securely at the hip level. The torque generated during an isometric contraction of the back
muscles is measured with a nylon harness positioned across the shoulder region of the back. Sensitive load cells attached to this harness measure the forces produced as the back muscles contract.

A visual display unit, positioned at eye level in front of the subject, supplies a percentage of the maximum voluntary force that the subject can generate. The percentage of maximal force displayed to the subject can be set for low, medium, or high levels of muscle contraction to measure the back muscles under different loading conditions. This feedback display is necessary to help the subject maintain an acceptably constant force output. The force information, together with myoelectric signals detected from an array of surface electrodes attached to the back muscles, is stored and processed using a small computer.

Mechanisms of Cervical Spine Injuries

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Purpose—The purpose of this project is to produce clinically relevant instabilities in the cervical spine specimens under controlled high speed trauma. Three-dimensional instability measurements are made before and after the trauma. The injuries produced are documented by X-rays and CT scans. During the trauma production, complete load vector applied to the specimen is recorded by a computer while the 16 millimeter movie monitors the deformation pattern. This is done at the rate of 3,000 frames per second. The main goal of the project is to relate the roentgenographic appearance of the fractures with its quantitative three-dimensional instability.

Progress—All the equipment needed for the trauma production and recording has been constructed and is functioning. It consists of the trauma-producing apparatus, multi-dimensional load cell, data recording computer system, and a 16 mm high speed movie. All the components are coordinated by a control unit. The three-dimensional stability measurement apparatus is also ready. Preliminary studies using canine spine specimens and a few human spine specimens of the cervical spine region have been completed.

Preliminary Results—Several animal and human spine specimens have been successfully tested through all the phases of the experiment. Compression-flexion loading has been studied. The maximum load vector for the cervical spine specimen (C4-5) was 3500 N of compression, 50 Nm of flexion moment and 500 N of shear force. The total duration of the load vector was about 10 ms. One of the most interesting results was the differential instability produced in the specimen for different degrees-of-freedom of movement. In other words, due to trauma there was a significant increase in the instability for axial rotation and flexion while the change in the lateral bending instability was minimal. This differentiated information concerning three-dimensional instability of an injured spine will be clinically helpful in designing optimum surgery and external support for a given fracture.

Future Plans—The preliminary studies using canine cervical spines will be continued. Thirty specimens will be traumatized in flexion-compression, extension-compression, and pure compression loadings. Immediately following the canine study, the human cervical spine study will be completed using the same protocol.
C. Human Locomotion and Gait Training

Gait Analysis By Use of an Instrumented Treadmill

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Purpose—The instrument for gait analysis is a treadmill permitting an unlimited length of gait. The treadmill is constructed to perform continuous measurements of the ground reaction forces for each foot. The measurements are processed on a PDP 11/10 computer. The output is a series of information: force curves of each of the three-dimensional vectors of each foot, average curves of the forces, calculation of ataxia, and calculation of the external work of each foot are computed. A typical gait analysis is based on 60 seconds of continuous gait. Studies of normal and pathologic gait have previously been published.

At present, studies of uphill and downhill walking are performed. The influence of total hip replacement on gait is investigated as well as different types of orthotics and prosthesis.

The Muscular Biomechanics of Human Posture

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Purpose—Persons with paraplegia need to regain functional use of their legs. An essential prerequisite for this is the restoration of upright posture, as the maintenance of posture is fundamental to movement. The human body is naturally unstable in the standing position, and upright posture is sustained with the fine coordination of many muscles. An understanding of the biomechanics and muscular coordination of posture is requisite to designing functional electrical stimulation (FES) systems for paraplegics in regaining leg movement.

FES is potentially a useful method for restoring upright posture in paraplegics. For FES to be used effectively, we must know which muscles to stimulate and how they should be coordinated.

Experimental research on posture suggests that muscular coordination is simplified by the organization of muscles into groups, with muscles in each group working together as a muscular synergy. The experimental identification of synergies is limited, however, because experiments are unable to discriminate between the activities of nearby muscles and are unable to monitor the function of deep muscles.

An engineering model can give much insight into the muscular biomechanics of upright posture. It is hypothesized that the muscles used in synergies are consistent with those used to maximally accelerate the body from a disturbed position toward the upright standing position.

Progress—An engineering model, based on the properties of the musculoskeletal system, has been developed. The body is represented as four rigid segments: foot, shank, thigh, and torso. The musculoskeletal system is modeled in detail, and 14 muscles of the ankle, knee, and hip are included. The muscles are represented by a generic dimensionless musculotendon model, and this is scaled to each muscle/tendon by the muscle strength, muscle fiber length, and tendon slack length.

The engineering model considers body posi-
tions from forward and backward swaying, with the knees fully extended and the feet flat on the ground. Optimization techniques are used to identify the functional significance of different muscles, their organization into synergies, and the body positions in which each synergy is effective. Additionally, optimization is used to determine quantitatively the significance of the various physical constraints, such as keeping the feet on the ground and keeping the knees fully extended.

The computer model has been developed and thoroughly tested. Preliminary results predict muscular synergies that are consistent with experimental work. Because muscles can only pull, and not push, the different muscular synergies are effective in only certain of the body positions.

For example, two synergies come into play in the lower limb: synergy I, using muscles on the front side of the body, and synergy II, using muscles on the back side of the body. Each synergy is used over a different range of shank and torso angles. The results identify the separate contribution of muscles such as soleus that have been neglected or grouped with other muscles in previous work. Also, the optimization results provide insight into the specific way in which posture is recovered. For example, should the upper body recover first, or should the leg? In general, it appears that the physical constraints severely restrict direct acceleration toward the upright position. Insufficient muscle strength does not seem to be a primary problem. The major difficulties are keeping the feet flat on the ground, due to the short length of the feet, and in keeping the knees in the fully extended position. Currently we are relaxing these constraints to investigate their effects on muscular synergies and the ability to accelerate toward the upright position. Additionally, the results of this work is being prepared for publication.

Effect of Shock-Absorbing Materials on Heel-Strike Forces

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Purpose—Researchers have shown a correlation between degenerative joint disease and the ability of the musculoskeletal system to absorb shock. The purpose of this investigation was to develop a system capable of monitoring the force between the heel and the shoe and then to determine the effect of different shock-absorbing materials on these forces in hope of finding possible candidate materials that may aid the arthritic in combating pain and further joint degeneration.

Progress—The system that was developed consists of three components: a transducer heel-pad, a Cyber Systems MicroDAS data acquisition subsystem, and an IBM PC XT personal computer. The instrumented heel-pad was made of eight lead zirconate titanate piezoelectric transducers bonded to a sheet of conductive silicone elastomer embedded in common RTV silicone rubber. Lead wires from each transducer were cabled to the MicroDAS, where analog signal conditioning was performed. Data acquisition control and data analysis were performed by the personal computer.

Fifteen healthy young adults, 10 male and 5 female, were studied. A series of 10 runs (a control run and 9 candidate material runs) was used for each subject. Relative measurements of force and impulse were taken during each run for all subjects. Significant improvements, as compared to the control, in force and impulse for each subject were calculated using Tukey’s Honestly Significant Different Test, a conservative comparison between means. Comparisons between subjects were performed using the Kruskal-Wallis test and a modified conservative rank comparison procedure.
Statistical comparisons showed that there were no significant improvements in force ($H = 13.45, p > 0.143$) or impulse ($H = 14.13, p = 0.118$) for the female subjects. Similarly, there were no significant improvements in impulse for the male subjects ($H = 14.30, p > 0.112$). However, significant reductions in the heel-strike forces of the male subjects were noted with four materials ($H = 38.65, p < 0.001$). In order of average rank, these were: Pelite, Frelonic, Firm Density Plastazote, and Viscolite.

Foot Interface Pressure Study

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Purpose—This study focused on the clinical treatment of the insensate foot and means to protect the plantar surface having or not having ulcerations. The purposes of this multi-fold project included the following: 1) investigate the suitability of various commercially available, heat-moldable plastic foam materials to redistribute plantar pressures; 2) determine relevant physical properties of plastic foam materials; 3) map vibratory perception thresholds on the foot and leg among diabetic patients; and 4) attempt to determine an at-risk boundary among diabetic patients.

Progress—The load-bearing characteristics of selected polyethylene foams were determined and described in terms of structural and compression properties. Based on this analysis, it was concluded that for the not-at-risk patients who do not require a high degree of plantar pressure redistribution, unmolded, small-cell, foamed polyethylene insoles are satisfactory. Further, issuing four sets for daily change allows insoles to recover from temporary compression set. For “at risk” patients without ulcers, molded bilaminate insoles were issued for maximum pressure relief. The “at risk” patients with noninfected ulcers, on the other hand, required two stage treatment: total contact cast during ulcer healing followed by thick heat-molded insoles and sandals while scar tissue matures. Vibratory perception data measured with a Bio-Thesiometer (Bio-Medical Instruments Co., Newbury, OH) were gathered on 167 patients presenting at the Diabetic Foot Clinic. Of this group, data of 90 individuals were deemed unusable in an analysis of vibratory sensibility for reasons of nonreliability or insensitivity unrelated to diabetes (i.e., secondary to alcoholism or chronic anemia). A statistical analysis of the 77 satisfactory data sets revealed a strong correlation between age and history of plantar ulcer development to vibratory threshold levels. A weaker relation was noted for years since onset of diabetes. Established was an 83 percent chance of predicting at-risk of ulcer development based on the values of selected vibratory thresholds.

A paper entitled “The Load Bearing Characteristics of Polyethylene Foam: An Examination of Structural and Compression Properties,” was submitted for publication. This paper is an overview of those properties of cellular foams that may be useful in the determination of the function of a particular material in load-bearing applications.

The project was completed and a final report has been prepared.
Purpose—The objectives of this study were to establish the aspects of crutch-assisted swing-through gait of persons with paraplegia that are energy intensive and to determine whether ways might be achieved to reduce energy expenditures. The hypothesis was that efficient crutch ambulation is feasible for the paraplegic ambulator.

Crutch walking gives increased mobility to a person with paraplegia. Curbs, stairs, or rough terrain do not limit access. Crutches take up less space than wheelchairs and can be used easily in unmodified offices and homes. They permit more easy access to public transportation than wheelchairs do. Crutches put the user at eye level with peers and may increase a person's morale and physical well being. On the other hand, the types of crutches typically used require high levels of energy. They increase risk of falling. And a wheelchair is capable of faster speeds at much higher efficiency on smooth surfaces. The ambulator must compromise with either system.

Establishing a technique for efficient swing-through crutch ambulation will provide the paraplegic ambulator with another option for gait modality. We believe it will be a long time before functional neuromuscular stimulation (FNS) systems can adequately provide dynamic postural control (balance) during ambulation. Therefore, even with sophisticated bipedal stimulation systems, crutches will likely be used. The gait modality of efficient and fast swing-through crutch ambulation would complement a bipedal FNS system as well as provide an alternative to wheelchair ambulation.

This study expands a preliminary investigation performed at this laboratory entitled "Kinematic and Pendular Aspects of Swing-Through Paraplegic Crutch Ambulation" (J. S. Rovick, M.S. thesis, Northwestern University, 1982). Rovick examined the kinematics of swing-through paraplegic crutch gait and modeled the gait with mathematical models that were based on physical principles. His work indicates three main areas of energy expenditure: 1) the energy required in stabilization of the joints (e.g., elbow and shoulder); 2) the energy lost in the muscular effort to elevate the body to allow the feet to clear the ground; and 3) the energy used to control the motion of the trunk. In this study, a major focus will be to try to eliminate the significant lifting of the trunk and legs to facilitate floor clearance during the swing phase. It is anticipated that by eliminating or reducing this expenditure of mechanical work there may also be reduction in the energy expenditure associated with control of the motion of the trunk. The plan is to utilize both crutch lengthening (via a rocker modification of the crutches) and leg shortening (via ankle control) as a means of facilitating ground clearance without energy-intensive lifting. The models of Rovick will be modified and used as conceptual design tools.

Evaluation of the normal and modified swing-through gait of subjects with paraplegia will be done by calculation of the mechanical work done during ambulation from the basic definition of mechanical work (the product of joint moments and joint velocity). The validity and sensitivity of this technique will be established. To obtain useful results in this study, it has been established that high-accuracy, high-sampling-rate positional data are required along with measurement of feet and crutches floor reaction.

Progress—The collection of data during clinical walking trials has been delayed during the development of a motion analysis facility based on the CODA-3 Movement Monitoring Instrument and utilizing two biomechanics platforms. This development work will be completed soon.

It is hoped that the feasibility of reducing the energy demand of swing-through crutch
ambulation by persons with paraplegia can be established and that a technique with the clinical potential of achieving ambulation in persons with paraplegic can be realized.

Weight Transfer Using Biofeedback

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Purpose—This study was designed to characterize changes in gait and balance after a 3- to 4-week rehabilitation program in an inpatient control group of adult hemiplegic subjects and to compare these changes to those of a matched experimental group who receive specialized biofeedback balance retraining.

Progress—To date, 40 control subjects and 8 experimental subjects have participated in the study. Both groups received physical therapy for 1.5 hours daily, 5 days a week. While the control group received standard therapy, the experimental group received an hour of biofeedback retraining. Biofeedback provided an immediate video display of the relative distribution of body weight carried by each limb during standing. Measures of gait and balance were collected before and after the therapy program. Footswitch and forceplate data were used to quantify the change. Multivariate analyses (Hotelling’s T^2) were used to evaluate the pretest-posttest differences in the control group. Multivariate analysis of variance will be used to evaluate differences between control and experimental groups when data collection has been completed with the experimental group.

Preliminary Results—In the control group, dependent measures of the total gait cycle (e.g., velocity, gait cycle time) changed significantly (p = 0.004), whereas dependent measures of the gait cycle segments (e.g., single- and double-limb stance times), symmetry (swing time ratio between limbs), and support through an instrumented force cane, did not change (p > 0.05). Although dependent measures of balance (e.g., center of pressure variability and deviation) changed significantly (p = 0.01), this was due to increased stability on the less-affected limb. The current hypothesis under investigation postulates that biofeedback training will achieve greater symmetry in balance and gait than was seen in the control group. Preliminary results indicate that following biofeedback training, subjects do learn to bear weight more evenly in static standing and when attempting even weightbearing.

Gait, Balance and Symmetry in Hemiplegia: An Analysis With and Without Biofeedback Retraining

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Purpose—Movement and balance deficits seen in the hemiplegic adult have been well documented, but few studies have reported the change that occurs in gait and balance following an intensive rehabilitation program. Furthermore, it is generally accepted that retraining balance and weight shifting ability will affect the quality of gait in this population. This relationship has not been substantiated in the literature.

The present study was designed to characterize changes in gait and balance after a 3- to 4-week rehabilitation program in an inpatient control group of adult hemiplegic subjects and to compare these changes to those of a matched experimental group who receive specialized bio-
feedback balance retraining.

Progress—Forty control subjects (mean age, 53.6 years; mean time from onset, 7.1 weeks) and 20 experimental subjects (mean age, 51.5 years; mean time from onset, 7.7 weeks) participated in the study. The subjects were selected according to the following minimum criteria: 1) no outstanding medical complications other than the CVA; 2) long-range rehabilitation goal of ambulation; 3) ability to stand without external support for 30 seconds; and 4) consent to participate. Both groups received physical therapy for 1.5 hours daily, 5 days a week. While the control group received standard therapy, the experimental group received from 45 to 60 minutes of biofeedback retraining per day. Biofeedback provided an immediate video display of the relative distribution of body weight carried by each limb during standing. Measures of gait and balance were collected before and after the therapy program. Footswitch and force plate data were used to quantify the change. Multivariate analyses were used to evaluate pretest-posttest differences in the control group. Preliminary analysis of experimental group data is descriptive at the present time, although multivariate ANOVA is planned for group comparison.

Preliminary Results—Gait was analyzed in highly correlated clusters of dependent variables reflecting measures of the total gait cycle (velocity, gait cycle, stride length, cadence), the relative gait cycle components (single-limb and double-limb stance times), and gait symmetry (swing to swing, stance to stance, and stance to swing ratios). Results from the control group indicate that whereas dependent measures of the total gait cycle changed significantly ($p = 0.035$), dependent measures of the relative gait cycle segments, symmetry, and support through an instrumented force cane did not change ($p > 0.05$). Although subjects were able to walk faster as a result of rehabilitation, interlimb coordination remained unchanged.

Balance was analyzed in highly correlated clusters of dependent variables reflecting measures of the position of the center of pressure (CP) in relation to the base of support (CP lateral and anterior-posterior), and stability in that position (variability/second lateral and anter-posterior, mean deviation lateral and anterior-posterior). Results from the control group indicate that although dependent measures of stability changed significantly ($p = 0.0002$), position of the center of pressure remained shifted toward the uninvolved limb ($p > 0.05$). Following rehabilitation, subjects demonstrated improved stability on their less-affected limb. The hypothesis under investigation suggests that biofeedback training will achieve greater symmetry in gait and balance than was seen in the control group. Preliminary results indicate that following biofeedback training, subjects do learn to bear weight evenly in static standing as well as when attempting even weight bearing. In contrast, gait symmetry remains unchanged as compared to that of the control group.

These preliminary findings suggest that with specific biofeedback training, hemiplegic adults are able to achieve improved static standing symmetry, but the results raise questions regarding the appropriate training techniques necessary to affect interlimb symmetry during locomotion.

A Modular Gait Analysis System

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Sponsor: The Northern Ireland Department of Health

Purpose—The aim of the project is to provide a modular, portable, low-cost gait analysis system suitable for clinical use. It is based on the Musgrave Park “Foot Pressure Profile Platform,” which is a low-profile platform containing 512 load cells that gives information about discreet
areas of foot pressure. These cells provide data that are stored in a low-cost computer. Two such platforms provide information about stride length. The data provide a monitor display and also can be analyzed. Additionally, an electrogoniometer system has been produced, recording the movements of six joints, and the data have been integrated into the computer. This information provides an analysis of the gait cycle.

Progress—To date, in addition to the raw data, the system provides an analysis of the hip, knee, and ankle movements, the center of pressure under the foot, and the foot pressure/time relationship. The system is undergoing trials at present, in order to review the type of information needed by clinicians and to assess its method of presentation. Because the system is modular, different clinicians can select modules that are applicable to their problem, and they can be provided with software suitable to their needs.

Human Movement Monitoring System
to Study Posture, Walking and Jumping

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Sponsor: VA Rehabilitation Research and Development Service

Purpose—In order to assess a patient's musculoskeletal disabilities associated with posture and gait, it is necessary to record, simultaneously, the kinematic, electromyographic, and kinetic data from that patient.

The Selspot system, a three-dimensional monitoring system manufactured by Selcom Selective Electronic, Inc., is used to digitize and record traces of motion. It has proved to be a useful tool for recording experimental kinematics. However, the software supplied by Selcom for controlling the Selspot system took up the full resources of our PDP-11/34 computer, which meant that data collected from other sources during an experiment had to be recorded off-line on an analog tape recorder. Synchronizing that data with the Selspot data was difficult and increased experimental error by a significant amount.

In order to record kinetic, electromyographic, and kinematic data simultaneously with a single computing system, we needed to modify the Selspot software and the memory configuration of the computer.

Progress—Existing computer programs allowed us to collect and store 32 channels of kinetic and electromyographic data. By modifying the memory configuration of a Digital PDP-11/34 and the Selcom software, we were able to record kinematic and kinetic data with a single computer system.

Preliminary Results—Currently it is possible, with a single computing system, to record simultaneously the data from 20 peripheral channels and the Selspot system for a period of 5 seconds. We are in the process of writing programs that will initialize and start both systems with a minimum amount of input from the user. Steps are also being taken to allow the data to be displayed as it is collected, to confirm data acquisition.
D. Upper Limb Applications

Analysis of Hand Performance Patterns in Able-Bodied and Cerebral-Palsied Subjects

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Sponsor: Cerebral Palsy Research Foundation of Kansas, Inc.

Purpose—The objective of this research is two-fold: to develop standards of able-bodied hand performance patterns, and to develop task design and modification principles for neurologically impaired populations, based upon a comparison of these able-bodied standards.

Currently, no information has been published on the normal pattern of hand performance of industrial tasks. Expected differences between males and females and the difference between preferred and nonpreferred hands have been published for only a few selected manual tasks. If it is assumed that the man-made environment has been designed with at least an unconscious reference to normal ability, the comparison of the profile of a class of disabled individuals to able-bodied standards should indicate appropriate ways of accommodating to that environment.

Progress—Subjects for this study consisted of 92 able-bodied adults, 46 male and 46 female, and 47 clients of the Cerebral Palsy Research Foundation of Kansas (CPR).

The performance measurement system used was the Available Motions Inventory (AMI) test battery of 71 manual industrial tasks presented in an adjustable workstation. The test battery is repeated for each hand. Six major types of subtests within the AMI were used: switches, settings, rates, strength, assembly, and reach-reaction. Several of the tests are repeated in a variety of subject orientations.

Hand preference for each subject was empirically determined by averaging the performance scores for each hand separately. The hand with the higher score was labeled the superior hand. The one with the lower score was determined to be the inferior hand. Raw scores for the superior hand of the able-bodied group were normalized (mean = 0.0, standard deviation = 1.0). Raw scores for each of the 71 subtests for the inferior hand of the able-bodied group were then converted using the mean and standard deviation of the able-bodied superior hand performance.

Gender, hand preference, and type were examined for the able-bodied group, and a three-way repeated measures analysis of variance was performed. Subtests were ordered from the easiest (reach-reaction) to the most difficult (assembly) based on the average score of all subjects and both hands.

Preliminary Results—The direction of interaction between gender and test type can be seen in strength, reach-reaction, and assembly tests. Males performed relatively better on strength and reach-reaction, and females were relatively better on assembly. The inferior hand is differentially affected by the assembly test.

In hand and similarity-and-difference tests, the degree of similarity between each of the 92 subjects' superior and inferior hands was examined. Tasks that were performed well by the superior hand were also performed well by the inferior hand.

While a majority of the subtests indicate a significant difference between the superior and inferior hands, several subtests indicate that the inferior hand actually performs better.

Results—Subtests within the AMI repeated in several positions indicate a significant interaction between hand and position. Pairwise comparison of cell means indicate that the superior and inferior hands performed at significantly different levels for all positions except side/
lower/horizontal (SLH—to the side, at a bench top, horizontal orientation). In the SLH position, the superior and inferior hands perform at essentially the same level. Furthermore, a comparison of means shows that in SLH and CLH, test activities performed to either side and directly in front of the individual on a horizontal plane, differed significantly from other positions in which the test modules were presented in a vertical position. Finally, in the CLH position, in front of the subject at a horizontal orientation, the hands demonstrate their greatest difference.

In comparison with the able-bodied group, the cerebral-palsied subjects are more alike on reach-reaction and strength tests, and more different on the assembly test. Generally this implies that the simpler the task, the more an individual with cerebral palsy will perform like an able-bodied person.

The general conclusion is that there is a strong relationship between the pattern of performance of the superior and inferior hands, but that disabled individuals’ specific patterns are more pronounced than in the able-bodied population. The degree of association between superior and inferior hands can also be seen.

The average level of performance of the superior and inferior hands was also examined. It is evident that the average level of performance of one hand is a good predictor of the other. The disabled group could be classed as diplegic. The remaining group could be classed as hemiplegic in that the average level of the inferior hand is significantly lower than the trend established by the able-bodied population.

The difference between superior and inferior hand performance of the group with cerebral palsy was evaluated using a paired-t statistic. All subtests indicate that there is a significant difference between the functional level of each hand. The profile for the disabled group shows much less variability than does the able-bodied group. This is to be expected with a significant number of hemiplegic subjects in the disabled group.

These initial results indicate it is feasible to use the AMI database to develop general design principles for specific disability types. Research should be extended to include analysis of the position parameter for the disabled group. Other classes of disability should also be evaluated.

E. Other

Mathematical Models for Bone Inelasticity and Bone Damage

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Sponsor: VA Rehabilitation Research and Development Service

Purpose—The intent of this study is to establish mathematical models for the mechanical response of cortical bone in the domain of inelastic deformation. The focus is to develop a new constitutive theory that characterizes the inelastic behavior of bone as it experiences irreversible deformation due, at least in part, to the formation of microcracks and voids (collectively called “damage”). This theory, which would describe brittle modes of inelasticity, is intended to serve as a counterpart to the theory of plasticity, which describes ductile modes of inelasticity in metals.

The potential significance of such a theory relates to the following: Stress-induced remodeling has important implications in the practice of orthopaedics, because many orthopaedic procedures alter the forces applied to the skeleton. The rapid growth of implant surgery in recent years has caused concern about how the altered
stress and corresponding damage fields in bone near the implant will influence the long-term success of the implant procedure.

Clinical investigations have shown that a reduction of in vivo skeletal loading results in loss of bone mass (bone atrophy), whereas increased skeletal loading causes a gain of bone mass (bone hypertrophy). Bone atrophy and hypertrophy are believed to be directly related to the change in stress field (and corresponding damage) within the bone. In addition, bones tested in vitro to failure under monotonic and cyclic loading are found to contain considerable microcrack and void densities in the region local to failure, suggesting that such damage is a primary cause for the loss of structural integrity in the bone. It is apparent, therefore, that it would be useful to generate mathematical models that might reliably predict stress, strain, and damage fields in order to predict bone loss or gain as well as to assess the structural integrity of the skeleton.

The approach selected employs techniques of continuum thermomechanics to develop a thermodynamically consistent constitutive theory for characterizing bone inelasticity and bone damage. Characterization of the mechanical response in terms of thermodynamic potentials would provide an opportunity to study the interaction between the mechanical response and biochemical response of bone tissue.

**Progress**—A simple, one-dimensional, cumulative damage model has been developed using classical creep equations to model bone fracture. A three-dimensional extension of this model, incorporating a scalar damage variable, has also been constructed. Both such creep-based models are strictly mechanical models.

A general structure for thermodynamically based damage constitutive equations has been established. Specific functional forms for the thermodynamically based constitutive equations for bone have not yet been established. Moreover, an explicit mathematical representation of the coupling between the mechanical and biochemical responses of bone through the second law of thermodynamics has also not yet been established.

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**Bone Fatigue and Creep Damage**

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**Sponsor:** VA Rehabilitation Research and Development Service

**Purpose**—The mechanical behavior of cortical bone under conditions of cyclic loading (fatigue) and static loading (creep) has not been well characterized. The intent of this study is to develop a mathematical model, based on creep and fatigue damage accumulation, which will predict bone fracture under various loading histories. Normal bone growth and turnover, osteoporosis due to bed rest, hypertrophy in response to exercise, and fatigue fracture are influenced by mechanical forces. The exact nature of the bone “adaptive” response is not known; however, researchers have demonstrated that static loads in vivo can cause either no change in bone mass, or bone resorption due to necrosis, while fatigue damage in vivo produces marked hypertrophy.

Our approach is to study a variety of simple loading histories and then use the principle of superposition to predict the bone response to combined loads. When subjected to high loads, or to low loads over a long time period, the material will accumulate damage and eventually break. The nature of the accumulated damage is different depending on the type of load. The damage can be observed by looking at the fracture surfaces using a scanning electron microscope (SEM).

**Progress**—Machined bone specimens have been tested under a variety of loading conditions. Constant loads have been applied in both tension and compression until specimen fracture (creep-fracture). Fatigue tests have been per-
formed in tension, compression, and combinations of tension and compression. The results have led to a mathematical model which attempts to predict time-to-fracture by summing creep (time-dependent) and fatigue (cycle-dependent) damage.

Preliminary Results—Tensile fatigue and compressive fatigue results suggest that tensile cyclic loading creates primarily time-dependent damage, while compressive cyclic loading creates primarily cycle-dependent damage.

Future Plans—The next step is to use the results described to predict failure for combinations of cyclic tension and compression.

Mechanical Stress Influences on Cartilage Degeneration and Ossification

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Purpose—Osteoarthritis, or degenerative joint disease, is a crippling disorder associated with aging. Virtually every individual who lives long enough will experience the degenerative changes in the cartilage at the joint surfaces that are associated with this condition.

Although it is widely acknowledged that mechanical stresses play a critical role in the pathogenesis of osteoarthritis, the mechanics associated with degenerative processes in cartilage have not been established.

We have developed a general theory for the mechanical regulation of biological processes in the chondro-osseous skeleton which is based on optimization of local strain energy transfer. The form of this theory is indistinguishable from one based on an optimization of fatigue damage accumulation in multiaxial loading states, yet is compatible with any proposed stress-induced stimulus (e.g., stress-generated potentials). This theory can be used to describe and predict the biological events associated with cartilage degeneration and ossification throughout life, beginning with the embryonic cartilage anlage.

We propose that biochemical processes of the chondro-osseous skeleton are driven to a major extent by the strain energy that is transferred (or dissipated) during intermittent mechanical loading. The ossification of cartilage will proceed based on the magnitudes of strain energy transfer rates (energy transferred per day). Cartilage degeneration and ossification will be slow in low-energy-transfer areas (e.g., all growth plates) and will be inhibited in areas of high, intermittent, compressive hydrostatic (dilatational) stress (e.g., articular cartilage and most growth plates). Once ossification occurs, the bone density and orientation will be modulated to provide an optimum level of strain-energy transfer rate at all sites, using the minimum amount of bone.

Progress—Four finite element models representing the proximal femur and hip joint have been generated, and more than 50 analyses with different loading and material properties are being conducted. The first model is a 2-D linear representation of the fetal cartilage anlage. The effect of intermittent daily loading on the cumulative strain energy transferred is simulated by superimposing the distributions of the stored strain energy imposed by a representative spectrum of loading conditions. The energy transfer rate is assumed to drive the process of ossification. The anlage material properties are successively changed to reflect mineralization as predicted by the contours of energy-transfer rate. In this manner, the entire growth and maturation of the femur at different stages of skeletal maturity are modeled.

The stress states and strain energy in the adult hip joint are further studied with a 2-D nonlinear-contact model of the joint and a linear 3-D idealized model of the femoral head.

Preliminary Results—The pattern of primary ossification and the formation of the diaphyseal
The Influence of Exercise on the Regulation of Bone Density

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Purpose—Skeletal mass and bone density measurements of selected trabecular bone sites are often used to assess the condition of the skeletal system. The variety of body sizes and types makes the interpretation of these absolute numbers difficult. Attempts to normalize these variables with respect to physical size have not been and cannot be successful. Beyond body size and other hereditary influences, factors identified as regulating bone volume include activity level, exercise, sex, diet, race, and hormone levels.

Proper correlation between these variables and skeletal response is needed to identify the forces of remodeling and guide clinicians in the development of programs to prevent, reverse, or slow the loss of bone with aging. Early detection and prevention of osteoporosis requires a quantitative understanding of the environmental factors which influence bone metabolism. If we can predict densities for various activity levels and exercises, then we have a mechanism for early detection of osteoporosis. We also suggest that prevention may take the form of exercises tailored to promote and maintain high bone density throughout one's life.

The overwhelming body of clinical and experimental evidence suggests that for healthy young persons, activity level and certain types of exercise are the dominant factors in bone metabolism. Athletic activities which involve significant increases in joint loads increase bone mass in the heavily loaded bones. (the humerus of the playing arm of 84 world-class athletes showed pronounced hypertrophy; cross-country runners were found to have a 20 percent greater calcaneal density than a nonexercising control population. On the opposing end of the loading spectrum, removal or reduction in the level of physical activity through immobilization or bedrest has consistently resulted in severe bone resorption.

However, numerous bedrest studies have included exercise protocols to test the hypothesis that forces on the body regulate skeletal mass, and none of these was successful in reducing the level of bone loss. That fact has caused some to question the role of exercise in the regulation of bone metabolism. We find no contradiction in the results, and suggest that the problem lies in the misunderstanding of what constitutes exercise for the bone tissue.

We hypothesize that bone in a state of equilibrium must be a unique function of a daily remodeling stimulus rate which is itself a function of the load history. Thus, if one suddenly increases (decreases) his/her level of physical activity, the daily rate of applied stimulus is increased (decreased), and bone will establish a new equilibrium density.

We further hypothesize that bone density is precisely modulated to provide the bone tissue with a constant level of stimulation. Since body weight, height, daily activity level, and exercise all contribute to the loading history, the daily remodeling stimulus becomes a...
fundamental variable for bone density normalization.

Progress—We have selected accumulated daily cellular microdamage as an appealing first choice for the remodeling stimulus. It forms a convenient method for condensing a complex load history into the weighted summation of two essential parameters.

Equations for damage accumulation were developed for differential bone volumes to obtain density ratios as a function of the change in local remodeling stimulus. Integration of these relationships over the entire bone volume resulted in equations which yield a bone density scale factor as a function of an external load scale factor. A set of activity levels for the calcaneus was constructed which encompassed near immobilization to vigorous athletic activity.

Preliminary Results—Expected bone densities for each activity level were calculated and compared to the literature with excellent results. These results have immediate clinical relevance which we are addressing. Stated briefly, high cyclic loads are the most effective means of increasing bone density. Jogging, which does not develop high loads, is not very effective in terms of the time spent exercising. For example, we predict that jogging 4 miles per day will increase calcaneal density by only 5 percent. Since ground-reaction loads attenuate vertically, the benefit to the axial skeleton and upper limbs will be even less.

Future Plans—We are currently combining the results of this work with earlier work done by our group. Our intention will be to demonstrate the equivalence of fatigue damage accumulation and a more fundamental energy term expressed as an effective stress.

Prediction of Cancellous Bone Apparent Density and Orientation

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Purpose—Normal activities cause cyclical loadings which may lead to application of a physiologically normal average stress state for all regions of cancellous bone. Since the observations of Wolff and von Meyer, it has been generally accepted that the trabecular orientation and apparent density of cancellous bone are functions of this average stress. However, the exact relationship between stress and bone remodeling is not known.

The ability to predict the response of cancellous bone to applied stress is critical to the evaluation of new prosthesis designs. If the bone response to implantation of a new prosthesis could be accurately predicted, expensive experiments could be avoided. The reliability of joint prostheses would be greatly improved and the time required for design and testing of new design concepts dramatically reduced.

While the exact relationships between applied stress and cancellous bone morphology are not known, two hypotheses have been put forward:

1. The direction of the bone trabeculae is parallel to the predicted principal stress directions; and

2. The apparent density (bone mass per unit volume) is related to the relative sizes of the principal stresses, as a function of the von Mises stress. These hypotheses have been tested. The first has been strongly supported, but the second has been shown to only be true under certain restrictions.

To unify the two hypotheses and remove the restrictions on the second hypothesis, we assume that cancellous bone is an anisotropic material and hypothesize that it has two goals; first, to maximize its structural integrity, and second, to minimize the amount of bone tissue. The attempt to meet these conflicting goals simultaneously leads to a unifying optimization principle governing the remodeling of cancell-
lous bone. This new theory predicts both trabecular orientation and density.

**Progress**—To determine the best orientation for the bone trabeculae and the minimum bone apparent-density needed to carry the stresses, we use a single optimization principle. Stated generally, the principle assumes that there is a relationship among stress, bone apparent density, and orientation of the anisotropy of the bone, and that this relationship measures how well the bone meets the conflicting goals of the bone growth hypothesis. Using special forms of that relationship, we have shown that the optimal orientation for the bone is with the trabeculae (anisotropy) aligned with the principal stress directions—just as is observed in living bone.

We have also determined a relationship between bone density and stress, making it possible to predict bone density from stress analyses. It seemed that the relationship between stress, apparent density, and bone orientation governing the remodeling of cancellous bone might be the amount of energy stored in the bone tissue due to its deformation under load. Using this stored energy approach, the function governing bone optimality is the strain energy density (SED) of bone tissue in the cancellous bone. Using the SED to determine the apparent density of the bone, we derive the relationship that bone apparent density is proportional to the square root of SED where the SED is evaluated for a reference density.

**Preliminary Results**—The SED in the bone can be found using finite element analysis. We have conducted a three-dimensional finite element analysis of the femoral head and neck and have predicted the cancellous bone apparent density in the femoral head. The resulting predicted density patterns are similar to those found in real femoral heads. This is the first time that cancellous bone's apparent density has been predicted in three dimensions. Therefore, this new theory is seen as a promising step towards the ability to predict accurately the changes in cancellous bone following implantation of a joint prosthesis.

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**Development of a Musculoskeletal Model of the Human Lower Extremity**

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Sponsor: VA Rehabilitation Research and Development Service

**Purpose**—Computer simulation studies of the human neuromusculoskeletal system are needed to understand the function of different muscles during movement. Thus, a musculoskeletal model of the human lower limb must be developed to study intermuscular coordination of even such apparently simple movements as standing and walking.

In addition to their use in studying muscle coordination as it occurs in able-bodied persons, musculoskeletal models can also be used to determine how to compensate for lost muscle function in disabled persons. For example, they can help determine which muscles should be stimulated and what activation pattern should be used to achieve standing and walking. This will aid in the design of functional electrical stimulation (FES) systems for persons with paralyzed lower limbs.

**Progress**—We have developed a musculoskeletal model of the human lower limb to study muscle function in the sagittal plane. With our model, we have completely specified the muscle parameters and musculoskeletal geometry for 24 muscles acting at the hip, knee, and ankle joints.

We have found that the range of joint angles over which a muscle generates torque is unique. By characterizing the torque-producing capability of each muscle, our model provides a basis for understanding intermuscular coordination in both able-bodied persons and in disabled persons using FES.
**Future Plans**—In the future, we plan to expand the model to study muscle function in the frontal and transverse planes. Because the muscle parameters are scalars and the musculoskeletal geometry is already specified in three dimensions, only the joint models need to be modified.

Also, the metatarsophalangeal joint will be incorporated in the model to aid in the study of intermuscular coordination during propulsion.

**A Musculotendon Actuator Model for Use in Computer Studies of Neural Control and Biomechanics of Movement**

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**Sponsor:** VA Rehabilitation Research and Development Service

**Purpose**—Computer models of the neuromusculoskeletal system require a model of each muscle and tendon (musculotendon actuator) under study. Models of musculotendon actuators, when imbedded into musculoskeletal computer models, will have usefulness in studies of neural control, muscular coordination, energetics, and biomechanics of movement.

Because hardly any of the significant musculotendon variables can be measured in humans during movement, musculotendon actuator models are virtually the only means by which to gain knowledge of in vivo musculotendon action. A large number of muscle models have been proposed. They can be classified into subcellular models and mechanical (input-output level) models. The subcellular models are primarily used to study molecular and biochemical events and are too computationally complex for our study of coordination. The mechanical models could be used in our study, even though specifying model parameters for each muscle would be a major problem, but most of them fail to take into account the effects of tendon, which is an important part of the musculoskeletal system.

Our goal is to construct a new, computationally efficient model of muscle mechanics that takes tendon explicitly into account and that can be scaled by a small number of parameters to represent a wide class of specific musculotendon actuators.

Our approach to modeling muscle and tendon is to base the model on musculotendon architecture and fundamental mechanical properties of muscle fibers and tendon. The basis of this formulation is the arrangement of muscle fibers with respect to tendon (pinnation angle), the arrangement of sarcomeres within a muscle fiber and of fibers within a muscle, the mechanics of sarcomeres when passive and activated, the dynamics associated with excitation-contraction coupling, and the constitutive (stress-strain) properties of tendon. The model is to be structured so that its dynamics are low-order and dimensionless and so that it can also be scaled to emulate the force-length, force-velocity, elastic, and activation properties of muscle and tendon.

**Progress**—A dimensionless, first-order model of musculotendon contraction dynamics has been developed. Only three actuator-specific parameters (muscle strength, optimal muscle fiber length, and tendon slack length) are needed to scale the generic representation to a specific actuator. The musculotendon actuator model has been simulated on a computer, and investigations are ongoing.

**Preliminary Results**—We have shown that tendon can be a dominant factor in musculotendon mechanics and that the degree to which musculotendon properties are affected is muscle-specific, at least for human lower-limb muscles.

When muscle fiber orientation is considered, the model changes only in algebraic complexity, though another actuator-specific parameter is required.

We are developing a first-order model for the dynamics associated with muscle activation.
Thus, the complete dynamics used to describe musculotendon mechanics will be second-order. Finally, the current model can be amended for use in studies of functional neuromuscular stimulation.

Neuromuscular Control and Biomechanics of Pedaling and Jumping

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Purpose—Some motor tasks that pose challenging intra- and interlimb coordination problems can be studied relatively simply by using computer modeling techniques in addition to traditional experimental techniques. Presumably, these techniques when taken together will shed light on the energetics of the task (i.e., how the energy produced by the muscles is stored in their musculotendon actuators and transferred from one actuator to another and to the mass segments of the body).

If we can show that computer modeling and experimental techniques together lead to a better understanding of coordination than either technique by itself, we will thereby demonstrate the utility of computer models in studies of movement. The modeling approach could then be applied to more complex movements, including those of disabled persons. It may be possible some day to base rehabilitation strategies in part on computer-aided design methods.

Our approach in this research is to study the coordination and energetics of jumping and pedaling, using computer simulations and experiments.

Progress—Our first simulations employed a simple two-segment jumping model to investigate the rudiments of jumping dynamics and energetics and to evaluate various models of the musculotendon actuator.

We are currently developing a more sophisticated neuromuscular-control jumping model that includes 24 human lower limb muscles acting on four articulated body segments. The model allows muscle activation (coordination) patterns to be specified automatically (so as to satisfy an optimality criterion) or manually. We are also working on a version of this model for pedaling.

We are also developing a movement-monitoring system for use in experiments on human jumping, posture, and gait, and we are building a pedaling apparatus to study the neuromuscular control and biomechanics of interlimb coordination during common and novel pedaling tasks.

Preliminary Results—As a result of studying a one-muscle, one-degree-of-freedom computer jumping model, we have been able to define the essential features for modeling the musculotendon actuator. We found that the musculotendon actuator can operate in different ways. For example, in jumping from a squat, the quadriceps generates the work output needed to propel the body, whereas in jumping subsequent to a fall, the quadriceps acts like a spring, storing energy during the fall and then releasing it to the body during propulsion.

We are currently integrating all our models into a complex neuromuscular control model and investigating algorithms to compute optimal coordinated activation patterns.
Intermuscular Coordination of Mammalian Movement

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Purpose—Rehabilitation of persons with severe motor disorders demands an understanding of the neuromusculoskeletal control mechanisms involved in movement. However, from a neuromuscular point of view, even the simplest movements are very complex, and multijointed movements involving the coordinated action of more than one muscle are, at present, only poorly understood. The goal of this project is to develop techniques for quantitatively analyzing intra- and inter-limb coordination.

The computational and experimental techniques developed in this project should be useful in studying lower extremity motor tasks such as maintaining proper posture, walking, and pedaling in the able-bodied and the disabled. Furthermore, they should shed light on optimal strategies for motor rehabilitation, reconstructive orthopaedic surgery, functional neuromuscular control of paralyzed muscles, and orthotic and prosthetic design.

Progress—We are currently developing a musculoskeletal model of the human lower limb with three parts: a muscle model, a musculoskeletal geometrical model, and a multi-segmental dynamic body model. Each part is generic, and it will be possible to scale the model to match a particular person's anatomy and physiology. We are also modeling the interaction between the body and its environment for the specific tasks of jumping and pedaling, and we are integrating all the models to allow detailed simulation of intra- and interlimb coordination of human lower extremity muscles.

In parallel, we are developing experimental techniques for monitoring body motion, body kinetics, and muscle activity during jumping, standing, and walking.

The “White Knuckle” Technique for Studying Skin Behavior Under Load

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Sponsor: VA Rehabilitation Research and Development Service

Purpose—The problem of studying skin blood flow response to external loading, which is believed to relate to pressure sores, usually involves rather sophisticated instrumentation. In the work reported here, a much simpler technique is explored; it involves the whitening of a knuckle in the bent finger.

A simpler technique for studying skin blood flow response to loading, especially one involving simple finger-bending and length measurements, would offer the possibility of a clinically feasible screening test for identifying those patients who are more prone to pressure sores. This could be important in redistribution of nursing care to minimize the occurrence of pressure sores in VA hospitals.

When a human finger is bent at the knuckle, there is a whitening of the skin caused by stretching of the skin over the knuckle. This whitening seems to occur at a specific angle of bend for a given subject. The phenomenon is related to the classical engineering problem of the tension in a pulley cable, in which the tension is balanced by a corresponding outward pressure provided by the pulley. In the case of the finger, the tension in the skin produces a corresponding pressure on the knuckle which causes the blanching of the skin. It therefore offers a potential alternate method of applying known pressure loads to the skin in order to study elastic behavior and blood flow response—without measuring the flow itself.

Before embarking on any such set of experiments involving physical variables, it is
prudent to first carry out a dimensional analysis in order to be sure that we measure all of the important parameters and that we treat them properly in analyzing the data.

**Progress**—We have made preliminary measurements of knuckle angle and skin elongation on four able-bodied and four paraplegic male subjects and find that they all have essentially the same characteristic curve of elongation vs. angle, in the form of two nearly straight-line segments. In all cases, the slope changes rather abruptly at the angle at which the knuckle 'wrinkles' disappear, since this point represents the initiation of pure skin stretching.

**Preliminary Results**—Once the skin begins pure stretching, the slopes of the curves seem to be relatively consistent and are apparently about 20 percent (mean value) lower for the subjects with paraplegia, indicating that the skin has lost some of its elastic strength and therefore stretches more easily in the paraplegic subjects. It was also noted that knuckle whitening seems to appear consistently for the able-bodied subjects at an angle of about 90-to-100 degrees. The paraplegics, on the other hand, seem to show a later and less definite whitening.

The number of subjects tested so far is clearly too small to permit any valid conclusions, and systematic measurements of skin thickness and radius of curvature remain to be done.

**Bone In Vivo and In Vitro Stress and Strain Patterns: Influence of Age and Activity**

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**Purpose**—The objective of this study is to examine the effects of aging and activity on the bioelectric and biomechanical response of cortical bone from a wide range of animals.

**Progress**—Growing and adult rats were subjected to various activity regimens, including cage, hypoactivity, and hyperactivity. *In vivo* and *in vitro* biomechanical (bending and torsion tests) and bioelectrical changes associated with aging and activity level were assessed from measurements of bone strain and current. The former were determined from miniature strain gauges bonded to the bone surface, whereas the latter were measured using a noncontacting electromagnetic device developed in our laboratory. Histomorphometry of tetracycline-labeled cross-sections was performed in order to determine bone geometric properties and growth rates. Similar biomechanical and histomorphometric examination of long bones from normal growing primates (baboons) was performed in order to provide quantitative information on this larger animal group.

**Preliminary Results**—In normal growing animals, both geometric and material properties are regulated in order to maintain an optimal bone strength. In rapidly growing animals such as the rat, material changes dominate, whereas in slowly growing animals geometric changes dominate. Analysis of the fracture strength due to torsional loading of immature rat and monkey femora indicated that the torsional strength scales across a broad range of animal sizes in spite of differences in geometric and material scaling strategies. A fracture strength index $S_b = T/L$ was formulated, where $T = $ bone strength and $L = $ bone length. $S_b$ was found to increase allometrically ($Y = ax^b$) with animal mass, and an exponent $b = 0.93$ was obtained, indicating that bone strength relative to body mass may decrease slightly during maturation for these animal groups. $S_b$ therefore may be a common scaling factor by which growing animals modulate bone strength.

Both intensive exercise (> 0.5 km/day) and hypoactivity (simulated weightlessness) in the rat were found to induce bone hypotrophy
(length and girth) and resulted in significant decreases in structural and material properties during maturation. Moderate exercise (< 0.5 km/day) appears to have no effect on these properties when compared to caged controls. Both exercise and hypoactivity may alter the compressive forces on long bone epiphyses, the latter of which may have an optimal stress range for normal function. Stress-induced changes in bone piezoelectric properties may also play an important role.

Future Plans—Recently, we have developed a split-core, noncontacting electromagnetic toroid with which the magnetic field, created by stress-induced current flow (streaming potentials), can be measured in wet, intact long bones. Preliminary in vitro results indicate that a current potential of approximately 1.0 microampere is obtained during application of bending moments equivalent to the body weight times bone length of the animal. Examination of the effects of loading frequency, aging, and activity on both in vitro and in vivo current potentials and corresponding strain levels in future experiments may provide considerable insight into the process of bone adaptation.

A Model for Postural Sway

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Sponsor: Liberty Mutual Insurance Company

Purpose—When an individual stands erect, the body makes minor movements over the location of the feet. The human body is incapable of remaining perfectly still. Furthermore, the task of standing erect is in itself a considerably complicated task, which individuals accomplish with various degrees of ease. We are interested in understanding the mechanisms that control posture for the purpose of measuring and quantifying the amount of dysfunction in individuals with movement disorders.

Progress—Toward this goal, we have begun to measure and analyze the stabilograms of individuals. Stabilograms are the plots that describe the continual displacement of the center of pressure (sway) in the horizontal plane of the feet as an individual stands still. Stabilographic measures have been used for many years, but their usefulness has not lived up to expectations, mainly because the tracings thus obtained do not have a well-defined parametric behavior.

Our approach to modeling the behavior of the stabilogram is to consider the sway as a random variable that may be described by Brownian motion.

When the stabilogram is plotted as a variable of the diffusion equation that describes Brownian motion, the resulting curve suggests that the modeling approach is correct. We plan to continue studying the applicability of the model with the intention of extracting information concerning the control properties that govern postural sway.

Measurements of Postural Sway

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Progress—During the past 4 years, the NeuroMuscular Research Center has accumulated a large inventory of data describing postural equilibrium in healthy individuals and in patients with neurological disorders. The tests were conducted in our Motion Analysis Labora-
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We are currently reevaluating these data to test a new mathematical model for postural sway. Unlike standard methods of interpreting stabilograms, the results based on our model clearly emphasize differences in postural sway and provide a means of understanding the motor-control scheme that directs the movement. To further understand the model as a control process, we have also begun to apply mathematically generated “sway paths” to the model. The behavior of the model in response to different stochastic and nonstochastic processes, with and without boundary conditions, is being studied.

Additional tests have also been performed to study the intrasubject and intersubject variability of stabilogram data when fitted to the model. Preliminary results are favorable to developing this method into a clinically useful tool.

Visuomotor Effects on Postural Sway

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Purpose—Vision aids us in maintaining our upright balance or posture. It has other functions, however, that may be incompatible with postural control. By employing different eye movements, we know that our perception of visual field motion changes. This study sought to determine the influence that eye movement has on postural control. We predicted that only those movements that yield a stable optical array would improve postural stability. Quick, jerky eye movements called saccades satisfy this condition, whereas smooth-pursuit eye movements do not.

Progress—Subjects stood on a strain gauge force plate and moved their eyes at various frequencies of saccade and smooth-pursuit. Results of the study showed that saccadic eye movements yielded less sway than smooth-pursuit eye movements. This effect was independent of frequency and length of fixation time. Practically speaking, these results show that a person is more stable when his or her eyes are scanning the environment (saccading) as compared to following (tracking, pursuing) a moving object.

These results have important therapeutic implications. Many patients with neurological deficits and/or visuomotor palsies of vestibular dysfunction have balance disturbances. These patients require therapy to regain control over posture. This work gives us some meaningful insight into the methods by which visual intervention can become a worthwhile modality for such persons.

Gross Motor Behavior in Late Childhood and Early Adolescent Children with Down’s Syndrome

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Progress—Data collection for this study of motor behavior in children with Down’s syndrome was completed in fall 1985. A total of 62 children with Down’s syndrome and 20 of their normal siblings were seen. Thirteen other children with Down’s syndrome were seen at their homes. These children were part of an original group of 89 children with Down’s syndrome
who were followed for their first 3 years at the Children's Hospital Developmental Evaluation Clinic in Boston.

Data analysis is currently under way. The data set includes measures of motor skills, postural sway, and joint range of motion. Height, weight, pubertal stages, and indicators of obesity, as well as severity of congenital heart disease, will also be included in the analysis. This will allow us to examine the interrelationships of these variables using multiple regression. We will also look for relationships between early motor attainments, for which we have a broad database, and later will monitor performance.

**Visual Control of Step Length During Running**

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*Purpose*—If they are to be adaptive, movements produced by the motor system must be coordinated with features of the local environment. This is where visual perception has a role to play in the control and coordination of movement. Our research on this problem seeks to identify optical variables that are utilized to regulate specific motor parameters during the performance of coordinated action. For example, we have been studying the way in which step length during running is visually adjusted to ground-surface irregularities, such as oddly spaced patches of bare ground. By using the force platform in the NeuroMuscular Research Center's instrumented walkway, we were able to confirm earlier results indicating that runners alter step length by modulating a single gait parameter, the vertical impulse that they apply to the ground during stance. A simple model suggests that vertical impulse can be directly modulated by the visually perceived time before contact with upcoming targets. Rehabilitation programs might apply such research not only to retrain specific movement patterns but also to retrain the ability to use visual information to regulate specific parameters of action.

**Modulation of Tonic and Phasic Reflexes with the Skin**

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*Purpose*—The interplay of the basic and tonic components of the stretch reflex is essential for smooth and more controlled movement performance. The effect of cutaneous feedback information on this phasic-tonic interplay is not very well understood. This information is crucial for developing rehabilitation methodologies for patients with neurological disorders. It is also helpful in understanding movement performance in legally blind subjects who depend on afferent feedback (including cutaneous feedback) in their movement.

This report discusses the modulation of tonic vibration (tonic) and H-reflexes (phasic) of the upper limb muscles after desensitization of the skin.
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Progress—Flexor carpi radialis (FCR) H-reflex and biceps brachii (BB) tonic vibration reflex (TVR) were recorded as indices of the excitability of phasic and tonic MNP, respectively. H-reflex was elicited by 1 ms, 0.2-pps pulses for the median nerve at the elbow, and TVR was elicited by applying an air-driven vibrator on the biceps tendon at 80 pps for a period of 60 seconds. FCR and BB EMG and elbow flexion torque were recorded before and after desensitization of the anterior forearm (AF) or posterior forearm (PF) skin areas using topical anesthesia (10 percent xylocaine) or a placebo.

Preliminary Results—Desensitization of AF skin area resulted in significant (p < 0.05) facilitation of the FCR H-reflex and significant inhibition of the BB TVR and decreased flexion torque. This effect lasted for 30 minutes postanesthesia. No measurable changes were recorded in either reflexes or the torque after desensitization of PF skin areas or after the placebo.

These results indicate that cutaneous receptor afferent discharges of flexor skin area simultaneously inhibit phasic reflexes/motoneurons and excite tonic reflexes/motoneurons of flexor MNP. These results also suggest that there is a spontaneous ongoing activity from cutaneous receptors modulating these reflexes simultaneously. It appears that cutaneous receptor afferents play a major role in increasing muscle stiffness and damping responses to external perturbation, resulting in a more smooth movement performance.

Electromagnetic Modulation of Cellular Interaction in Natural and Foreign Enviroms in Bone

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Sponsor: None Listed

Purpose—The biology and function of the skeletal system including joint structures are singularly important. The repair processes of the articular cartilage are being intensively studied both in disease and in trauma in the attempt to prevent degenerative and rheumatic diseases and to rehabilitate various forms of disabilities. The objective of this study was to highlight the importance of research on pulsating extremely low frequency fields on osteoarthrology.

Cellular interaction in the osseous tissue involves at least two distinct mechanisms. In microhistological studies, osteoclasts responsible for bone absorption are seen directly in the vicinity of the absorption area. Osteoblasts in the active form are further away from where the bone is being actually laid down (until osteoblasts become osteocytes and cease production of osseous tissue).

The cellular interaction depends on the form of stimuli of:

a) Biochemical (antibiotic) cytotoxic drugs. The chemical structure of the biomolecules (e.g., fibrous and globular proteins) is function-related, and their diversified functions depend on the extensive range of structural conformations and flexibility prevalent in biological interactions. A relatively small drug molecule combines with functional groups (called receptors) of a macromolecule. The small drug molecule induces a change in the electrical charge distribution of the whole macromolecule, which leads to a change in the conformation, orientation, and function of the large biomolecule present either on the cell membrane or inside and outside of the cell. A platelet-derived growth factor (PDGF), structurally a protein, is also responsible for cellular growth at the tissue level on site, but its contribution is not quite certain.

b) Endocrinal/hormonal stimuli (e.g., parathyroid hormone, pituitary growth hormone).

c) Electromagnetic or bioelectrical signals (e.g., direct or induced).

d) Mechanical, traction, manipulation, or other movement, or lack of movement (i.e., rest and immobilization).

Here, we deal only with electromagnetic or
bioelectrical signals. The different areas of the electromagnetic spectrum have different biological interaction. The biocoupling of low-intensity, extremely low frequency (ELF), nonionizing, isothermal radiation has either a stimulating or inhibitory effect on cell metabolism.

Osteoarthritic people suffer from common ailments, moderate to severe pain, stiffness of various joints, lack of mobility or severe restriction of movements, and poor biological function as a male/female partner. The treatment with ELF and low-intensity electromagnetic irradiation of affected joints or parts of the body improves not only the symptomatology but also the quality of life. Apart from the subjective improvements, significant changes are noticed in the radiological appearances of the joints. This may mean that not just the arrest of an otherwise progressive disease but its reversal—at least in some cases—can be indisputably established from a series of radiographs.

Therapeutic applications include patients who are waiting for prosthetic operations. The curative role of pulsating electromagnetic radiation of low frequency and low intensity has been established. In the early cases of degenerative arthritis, patients were suffering from arthritis for the past 10 to 15 years and were not responding adequately to analgesics, anti-inflammatory, and nonsteroidal drug therapy. Unfortunately, conventional physiotherapy, including ultrasound/shortwave therapy, is not much help in most cases. The subjects are either on the waiting list or are prospective candidates for future replacement surgery.

Another therapeutic application is treatment ancillary to replacement surgery in advanced or late osteoarthritis of 15 to 30 years’ duration: a) preoperative treatment before prosthetic replacement of the diseased synovial joint for histological studies on replaced joints that have been irradiated by electromagnetic radiation before the replacement operation, the preparation for a better foundation for prosthesis to be embedded in the bones in case of widespread osteoporosis, and the improvement of revision rates and failure rates of the prosthetic operation in the treated joints; b) postoperative treatment to prevent early infection and movement of prosthesis as a prophylactic measure; or c) late or delayed treatment after hip replacement operation (e.g., in the same hip for osteoporosis or fracture complications, or in the contralateral hip for progressive osteoarthritis).

Still another therapeutic application is to prevent arthritic changes from developing in the adjoining synovial joints leading to replacement surgery at a later date, such as delayed or nonunion fracture cases involving joints with developing osteoarthritis and osteoarthritis as associated with grossly disabling soft tissue injury in ankle or knee or contracture of hand.

A final therapeutic consideration is for the palliative treatment for excruciating pain and progressive stiffness in already deformed, longstanding arthritic elderly subjects, (e.g., osteoarthritis in wrists where prosthetic operation has been ruled out). The objective is to improve the quality of life.

Preliminary Results—The mode of action is one of the intriguing subjects in modern bioelectrochemistry. Vital processes in the cells are associated with bioelectrical potential differences. The biopotentials are, in turn, dependent on the ion concentrations of the internal and external environments of the cells. The ion concentration varies as the rate of dissociation and recombination of ion pairs in solution. The intensity of the transport process of the cell membrane as well as the intensity of the metabolic processes inside the cells depend on the ion concentration.

More attention should be paid to the electrical characteristics (e.g., biopotential sensitivity leading to changes in the transport and metabolic processes in cells). In arthritis, evidence is accumulating of the altered metabolic activity of the cell resulting in changes in the biopotential differences, or vice versa. Thus, the measurement of biopotential differences can undoubtedly serve in estimating the intensity and nature of the metabolic processes in the cells.

This conclusion results from the parallel isotopic study, the electron-microscopic investigations, and the explanation of the electrical parameters of similar structures. For example,
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fracture studies show that the fracture site is persistently and consistently electronegative in relation to the undisturbed distal end of the same bone. This electronegativity of the interrupted bony tissue is reversed depending on the intensity of the healing processes; that is, the intensity of the metabolic activity of the different types of bone cells as demineralization or mineralization are taking place. In case of cartilaginous tissue affected by arthrosis, metabolic processes typical of cartilaginous tissue take place in early cases when treated, whereas more sclerosis is seen in late cases as evidenced in X-rays of the relevant joint surfaces and surrounding areas. It may mean for the future that it is possible to reverse the pathological processes in osteoarthritis cases and to control the aging process. The future thus holds promise for sufferers of degenerative or rheumatoid arthritis through the efforts of medicine, surgery, physiotherapy, and electrobiology.

Enhancement of Union of Segmental Defect Fractures

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Purpose—Large diaphyseal defects in long bones continue to challenge surgeons who deal with trauma, tumor resection, infection, and leg-lengthening procedures. Autogenous bone grafts require major surgical procedures with significant associated morbidity with only a finite amount of material available. New alternatives such as allografts, bone derivatives, and synthetic materials appear on the horizon. These alternatives hold promise but need further evaluation to compare their efficacy with currently available techniques of bone grafting. Because of variations between individual animals, the need exists for control of bone graft studies within the individual animal rather than comparison of results from animal to animal. This study was performed to define a bilateral diaphyseal defect model in a weight-bearing bone of the dog as well as to study the efficacy of morselized cortical bone as a bone graft material.

Progress—Sixteen adult true-bred foxhounds, weighing between 25 and 35 kilograms, were subjected to bilateral surgical procedures that created a 2 cm defect in the distal half of each radius. Periosteum was carefully excised and removed with each cortical segment. All defects created were stabilized with a single-bar tubular external fixator placed on the anteromedial surface of the foreleg. Eight control dogs had one side grafted with morselized autogenous cancellous bone obtained by curettement from the contralateral humeral head. The opposite side received no graft material. Eight study dogs were treated with morselized cancellous bone on one side and morselized cortical bone on the other side. Morselized cortical bone of a particle size from 250 microns to 2 mm was created by grinding the removed segments of cortical bone from both defects in a sterile grinder for 3.5 minutes. Prior to grinding the cortical bone, all soft tissue (periosteum and marrow) were meticulously removed. The dry weight of cortical bone used in each defect averaged 1.8 ± 0.2 grams for cortical bone and 0.8 ± 0.2 grams for cancellous bone. All dogs were allowed full weightbearing activity postoperatively. Serial radiographs were obtained to assess graft incorporation. Dogs were sacrificed at 12 and 24 weeks in both the control group and the study group. All radii were explanted and tested to failure on a Burstein-Frankel torsional testing apparatus. Histology was performed using a microscope. Nine normal radii from the same size and breed of dog were also explanted and tested to failure in torsion to give comparative data. Pin tract infections with the external fixator were a minor problem and required some adjustment in the technique and position of pin placement. These infections did not involve the bone graft site and were controlled by
local wound care.

**Preliminary Results**—Two dogs were lost because of early, overwhelming infection and were replaced with fresh animals. At both 12 and 24 weeks, the control group of resected, but not grafted, defects showed a 100 percent rate of nonunion radiographically. Morselized cortical bone graft also showed a 100 percent nonunion rate with no major difference in bone volume or histology when compared to the nongrafted defects. All cancellous bone grafts united rapidly and then consolidated. Results of torsion testing are reported in values of maximum torque to failure in the 12- and 24-week specimen. Cancellous grafts showed 30 to 50 percent of the strength of a normal dog radius. Morselized cortical graft and no bone graft demonstrated 0 to 10 percent of normal dog radii, whereas morselized cortical bone and no graft continued to show 0 to 10 percent of the normal dog radius, indicating a nonunion. The cancellous grafts had recanalized completely at 24 weeks and appeared as normal bone histologically. Radiologic evaluation demonstrated almost complete resorption of morselized cortical bone, which was confirmed by histology. Histology revealed the presence of a fibrous nonunion with an occasional pseudarthrosis in the defect and morselized cortical bone specimen.

This bilateral dog radius model provides a weightbearing bone in which a consistent nonunion can be created. At the same time, the stability of the bone can be controlled, allowing the animal normal activity. This model should be useful for the comparison of various new bone-graft materials and substitutes using the individual animal as a control. Cortical bone, alone, which is morselized by means of power grinding, has little or no osteoinductive of its own and should not be used as a bone graft material without the addition of some other osteoinductive material (bone marrow elements). Autogenous cancellous bone graft is an ideal bone graft material for diaphyseal defects even in the absence of periosteum. It has excellent osteoinductive capacity, is rapidly vacularized and incorporated, eventually consolidates, and then recanalizes to an appropriate strength level.