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VI. Biomechanics

A. Joint Studies

1. General

Joint Contracture: Biomechanical-Clinical Correlates

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Sponsor: National Institutes of Health
(National Institute of Arthritis, Diabetes, and Digestive and Kidney Diseases)

Current evidence suggests that stress-deprivation effects on soft tissues are profound and occur rapidly and that recovery from stress deprivation is quite slow. In this respect, recovery seems to parallel the effects of exercise on normal connective tissue. For example, our studies indicate that a large effort over a long period of time is required for a small hypertrophy increment of tendons or ligaments. The purpose of the proposed research program is to document further: (i) the fibrous connective tissue morphological and molecular changes resulting from stress deprivation, and (ii) the consequent alteration in physical characteristics. The answers to these questions are particularly important with respect to the development of the rationale for treatment and rehabilitation of soft tissue injuries, such as the knee ligaments.

A standard internal fixation model is used to induce stress-deprivation effects in rabbit knees. Capsular and ligamentous structures from the model are characterized by biomechanical, morphological, biochemical, and metabolic techniques on a progressive time base during the development of and recovery from the stress-deprivation state. Hormone or drug treatment effects are also evaluated for efficacy in modulating the development of and recovery from the stress-deprivation state.

Biochemical analyses employed permit evaluation of collagen turnover, total proteoglycans, and collagen cross-link quantitation (reducible and nonreducible). Light microscopy and transmission EM are also used to characterize matrix and cells as well as the ligament insertion sites. Biomechanical tests on ultimate strength and stiffness of bone-ligament-bone complex as well as the mechanical properties of the ligament substance are performed. In addition, arthrographic characterization of contracture strength is assessed.

Biomechanics of Ligament/Tendon Repairs and Grafts

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Sponsor: National Institutes of Health
(National Institute of Arthritis, Diabetes, and Digestive and Kidney Diseases)

It is our hypothesis that healing of ligaments and tendons is a long-term process that involves a return in strength due to callus formation followed by long-term remodeling of the collagen, involving changes in fiber alignment, ground substance, and cross-linking. We further hypothesize that the extent to which a blood supply is available has a significant effect on the return in strength. Repairs in relatively vascular regions and free grafts need protection for prolonged periods of time. On the other hand, the presence of a profuse vascular supply may permit a more rapid return in strength, allowing earlier motion, earlier rehabilitation, and return to normal activity with less disuse effects.

To test these hypotheses, we will measure the return in strength and biochemical remodeling over time of selected primary repairs and grafts in activity conditioned, skeletally mature beagles. The following specific situations will be studied.

Primary Repairs—(i) We will compare flexor-tendon repairs in highly vascular paratenon regions with repairs in the synovial sheath, a comparatively avascular region. (ii) An anterior cruciate mid-substance partial injury will be studied with and without the use of a fat pad sutured to the ligament to provide an additional source of blood supply. (iii) Healing in the medical collateral ligament will be determined for complete mid-substance tears induced at the time of surgery.

Grafts—(i) A bone-lateral tendon-bone free graft substitute for the anterior cruciate ligament will be compared with the same graft that incorporates a tissue flap that provides its blood supply. (ii) A flexor tendon autograft will be compared with an allograft.

In the first year, we will document the local blood

supply using microangiography and refine the surgical techniques, particularly to avoid interruption of the blood supply. We will also verify our existing gripping methods for mechanical testing of the isolated tendons. During the second and third years of the project, we will measure both the return in strength and the biochemical changes in each model.

2. Lower Limb

Evaluation of Joint Loading in the Use of Walking Aids in Total Hip Replacement Patients

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Abstract—The immediate result of total hip replacement surgery is a low-friction joint with acetabular and femoral components rigidly fixed in the pelvic and femoral bones respectively. However, soft tissue damage results in reduced abductor function as well as a general tightness surrounding the hip joint.

Postoperative care is a compromise; protection against subluxation of the joint and tearing of the abductor attachments versus the need to load the joint to reduce stiffness and bone and tissue atrophy. Surgeons vary in their prescription of therapy and walking aids (which range from walking frames to elbow crutches to stick). Some patients are encouraged to leave the hospital in 2 weeks with no aids, while it is recommended that others use at least one stick up to 6 months postoperatively.

The purpose of this study is to obtain biomechanical parameters of aided gait that can be considered when prescribing an aid and it use, in order to optimize patient mobility and joint protection.

The types of aids being studied are elbow crutches and walking sticks. Besides the type of aid, the technique used to measure for the length of the aid is being evaluated.

The analysis focuses on both the upper and lower limbs. The shafts of the aids are strain-gauged for determination of three forces. Particular attention is given to the loading of the shoulder girdle by combining the kinetics of the aid with the kinematics of the upper limb. The cuffs of the elbow crutches are also gauged to evaluate the contribution of the cuff in supporting the patient. The lower limb ground-reaction force is measured to assess the weightbearing relief which the aid is allowing. Other gait parameters such as stride length, velocity, and the duty cycle of the aid during the gait cycle, are measured as indicators of mobility.

Ankle Biomechanics

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Abstract—A computer model of the ankle system has been formulated which is based on a single, free-rolling bearing joint, with four muscle groups (giving nine muscles in all), and moments about two axes (producing plantar/dorsi flexion or inversion/eversion). The Strathclyde TV Gait Analysis System is used for the collection of data.

Data from patients suffering from hallux valgus were chosen to be tested with this model, as this condition is likely to have a great influence on the ankle dynamics.

Since hallux valgus is a common condition, various surgical procedures have been developed and used for its correction. Four of these procedures have been chosen for study (Keller's resection, Wilson's osteotomy, IMTP fusion, and sylastic prosthesis), before and after undergoing surgery.

Results should provide a better understanding of how patients with hallux valgus place their feet during walking and how this affects the ankle dynamics and leg-muscle forces. By analyzing data from patients undergoing the above four surgical procedures, the effectiveness of such treatments can be compared more quantitatively and objectively.

Clinical Biomechanics of the Knee: Rotation Laxities

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This project is directed at three major goals: (i) determining the function of knee ligaments in limiting internal/external rotations of the leg, (ii) improving the accuracy of diagnosing ligament injury associated with rotatory instabilities, and (iii) determining the appropriate attachment points and initial tension for biological grafts and prosthetic ligaments used to replace the cruciate ligaments.

Our methods employ a complete three-dimensional six degrees of freedom analysis of joint loads and motions. Four major projects will be conducted.

Ligament Restraints—The forces and moments developed by the ligaments in resisting internal and external tibia rotations will be measured. The effect of changing the location of the rotation axis will be investigated.

Clinical Examinations—We will measure, in cadavers, the effect of simulated ligament injuries two ways: by the increases in three-dimensional joint laxity under known loads and by changes in knee kinematics during each of the major clinical examinations used to diagnose injury. To apply our results to patients, a laxity examination table will be constructed incorporating an instrumented spatial linkage for measuring three-dimensional joint motions and transducers for measuring the force applied during the examination. The errors associated with skin mounting will be studied in cadavers, and a group of normal patients will be evaluated for anterior-posterior, internal-external, and abduction-adduction laxities.

Surgical Reconstruction—The total anterior-posterior laxity of intact cadaveric knees will be measured as a function of flexion angle and internal-external tibial rotation. The anterior cruciate ligament will be removed and the change in laxity recorded. Grafts will be implanted, varying the tibial and femoral attachments, the initial tension, and the flexion angle when tension is applied. Laxity surfaces will be compared to determine the conditions that best reproduce the intact knee.

Knee Modeling—Collaboration will continue with researchers at Ecole Polytechnique in Montreal, Canada, who are developing a finite element model of the knee with support from the Natural Sciences and Engineering Research Council of Canada. This study will provide experimental data on the mechanical properties of ligaments required by the model. At the end of the first year, the model will be implemented on our computers. The model will be validated and used to investigate instabilities under activity conditions.■

Ligamentous Knee Stability: Combined Clinical Loadings

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Sponsor: National Institutes of Health
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Ligamentous stability of the knee will be quantified in vivo and in vitro by (i) direct measurement of force versus displacement responses for anterior-posterior tibial drawer, (ii) moment versus rotation responses for varus-valgus angulation of the tibia, and (iii) torque versus rotation responses for internal and external rotation of the tibia. The stiffness and laxity data collected will quantify the contributions of knee ligaments to overall stability of the joint and help to improve the accuracy and interpretation of the clinical knee laxity exam. Existing test fixtures will be modified to study the complex responses of cadaveric knees to combined loading states on a MTS materials test machine, including the application of tibial-femoral contact force (joint load). The effects of knee ligament section and total knee replacement will be examined with this advanced methodology.

The UCLA clinical knee-testing apparatus will be modified to include measurement of anteromedial and anterolateral rotatory instabilities. Patients with injuries to their knees will be tested before and after their surgical reconstructive procedures to permit an objective assessment of their operative results. Patients who have received total knee replacements will undergo selected testing to evaluate the stability of their implants in situ.

A portable field testing apparatus will be designed and prototypes constructed for use in the UCLA clinics and Sports Medicine Center. These units will

expand our data collection capabilities and allow screening studies of varsity athletes prior to the competitive season in order to study correlations of knee stiffness and laxity with the incidence and severity of knee injury■

Pathokinesiology of Anterior Cruciate Ligament Deficiency

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Introduction—Rotational instability of the knee joint following rupture of the anterior cruciate ligament is recognized by many orthopaedists as a major problem in the active individual. In many persons, absence of this ligament leads to progressive instability, functional disability, and knee joint deterioration. To prevent this sequence of events, numerous technical solutions, including repair and/or reconstruction of the anterior cruciate ligament, and rehabilitative strengthening have been proposed. However, a significant percentage of patients with an absent anterior cruciate ligament have no functional disability and little or no objective instability. In these individuals, progressive instability and knee joint deterioration do not seem to occur.

The obvious discrepancy in the clinical course of patients raises multiple questions regarding the nature of the knee with an absent anterior cruciate ligament and the appropriate treatment for this deficiency. A major problem for the orthopaedist in attempting to evaluate the multiple alternatives available is an incomplete knowledge of the biomechanical alterations of the knee joint produced by an anterior cruciate ligament tear. In addition, little is known about the response of the patient to these alterations in order to compensate for this injury. Documentation of instability has been largely clinical in nature, based upon nonfunctional evaluations and using inexact descriptive tools. The inability to precisely describe the deficit involved has made evaluation of treatment modalities even more difficult.

Objectives—The objectives of this project are to define the knee kinematics and kinesiology in normal individuals and in the functionally compromised and functionally able patients with anterior cruciate ligament deficiency. The testing tasks are level walking, pivoting, and controlled exercising using gait analysis and isokinetic techniques. Information is collected using electromyography and total knee goniometry. This information is then subjected to extensive computer analysis to define abnormal motions, dissimilar synergy patterns, and abnormal variations in torque production that occur among the injured and uninjured groups.

By comparing these groups, compensatory mechanics might be identified that could influence the choice of surgical procedure, orthotic device, or exercise program. The analytic techniques could then be carried beyond the level of clinical investigative tools to an invaluable diagnostic, prognostic, and evaluative system for the anterior cruciate ligament deficient knee.

General Aims—The work plan will establish:

1. The kinesiology of the knee joint in terms of translational and rotational motions, the muscular synergies, and general body motion in two functional activities, level walking and pivoting;
2. The translational and rotational motions in two controlled conditions, internal-external rotation and flexion-extension.

The purpose of the controlled conditions is to stress the knee through its full range of motions since functional activities utilize only a portion of the full range. The following populations are being studied:

1. Patients with functional disability secondary to chronic anterolateral rotatory instability;
2. Patients with documented anterior cruciate ligament deficiency, but no functional disability;
3. Normal persons with no injury history.

Methodology for Knee Kinematics Measurement—Subjects are asked to:

1. Walk straight at free and fast speeds;
2. Walk straight and make a 90 degrees pivotal turn as they normally would at a speed of one meter per second;
3. Walk straight and make a 90 degrees pivotal turn and keep the pivoting foot planted (do not rotate over heel) at a speed of one meter per second.

Knee kinematics are measured using a 6 degrees of freedom goniometer and are acquired in real-time with a PDP11/03 computer sampling at 25 samples per second. Instantaneous and global screw motions are calculated; the reference posture for the global screw motion is the anatomic standing position.

Results—The anatomic and screw motions of ten uninjured and five injured people have been studied. The anatomic motions of all subjects were very similar. The measure that concentrates upon and demonstrates differences in kinematics is the instantaneous screw motion. The screw motions of uninjured knees and tight injured knees are remarkably similar to straight walking. However, during pivoting there are some major differences. The instantaneous screw motions of loose injured knees differ from those of uninjured knees during all four tasks■

Biomechanics of the Hip and Knee

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Sponsor: National Institutes of Health
(National Institute of Arthritis, Diabetes, and Digestive and Kidney Diseases)

Specific Aims

1. To investigate the effects of incorporating fiber length, fiber direction, and fiber type into our existing muscle model.
2. To investigate the effects of differing cost functions on muscle force predictions and to study the appropriateness of using differing cost functions for differing activities in normal subjects and in subjects with selected abnormal conditions.
3. To investigate, in a comprehensive manner, effects of varus, valgus displacement, and rotational proximal femoral osteotomies on three-dimensional hip joint forces.
4. To study the three-dimensional loads on the hip and knee during straight-knee lifting of a 20-pound load from the floor, bent-knee lifting of a 20-pound and 50-pound loads from the floor, jogging, tennis serve, and golf swing.

Objectives (Correlated to the Four Specific Aims)

1. We anticipate that this aim will be completed by the end of 1984.
2. We expect to complete all of the studies on optimization criteria within the first few months of the coming budget year as most of the groundwork is completed as described above. The remaining portion of this aim to be accomplished is to determine how pathological conditions affect the choice of optimization criteria. For this portion, we must collect data on a variety of subjects with pathological conditions (i.e., painful gaits, joint fusions, neurological deficits). This data will be collected in the coming budget year when the new Vicon system is operational. Once collected, the data will be input into our current programs and then we will determine the appropriateness of the various criteria based on simultaneously collected EMG data.
3. This work is completed as originally planned. We are considering the possibility of extending our work to take into account the alterations in the location of the knee center which can occur with the osteotomies.
4. Data for the final specific aim will be collected, analyzed, and reported within the coming budget year. We will select only one or two optimization criteria for the work, and the choices will be based on the sensitivity studies described above■

Mechanics of Human Acetabulum

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The objective of this study for the coming year is to better elucidate the stress fields in the acetabulum and tibial plateau before and after joint arthroplasty. The goal is to better understand the normal joint mechanics and to better evaluate and design artifical components.

Considerations will be given both to conventional cemented components and to new porous ingrowth components. Our methods will incorporate plane strain and equivalent thickness finite element models that will be implemented in such a manner as to make the evolution to future three-dimensional models a smooth transition. Some of our models will use a contact element approach in an effort to better stimulate in vivo loading.

The studies will parametrically examine the influence of geometry and materials. Special emphasis will be directed toward maintaining normal bone stresses and avoiding poor stress transfer characteristics at the component interfaces■

Biomechanics of Anterior Cruciate Repairs

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(National Institute of Arthritis, Diabetes, and Digestive and Kidney Diseases)

The goal of the proposed research is to better understand the mechanical factors in surgical repair procedures for chronic anterolateral insufficiency of the knee, where the repair requires an anterior cruciate substitute to be established. Experiments will be run on cadaveric knee specimens. Ligament forces will be measured by buckle force transducers on the four major knee ligaments. A six degrees of freedom goniometer system will be used to measure three-dimensional knee motion when the knee is subjected to a wide variety of external load directions.

Normal knees, knees with a simulated anterolateral injury, and knees repaired by one of eight procedures will be tested in an identical manner. Theoretical ligament lengths, and hence, loaded ligament states, will be predicted using already developed theoretical knee models with the measured three-dimensional motion as input. The influence of repair insertion location will be studied both theoretically and experimentally. The normal and repaired knees will be compared on the basis of anterior cruciate or substitute force magnitude, joint laxity, and load sharing by the other ligaments■

Proximal Femur Load Transmission in Early Childhood

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In spite of the extensive clinical resources devoted to management of hip disorders in children, there is an almost total absence of quantitative data regarding the mechanical structural behavior of the juvenile femur. We propose to conduct a detailed engineering investigation of the load transmission through the proximal femurs of normal children, ages 1 through 7 years.

In the upcoming funding year, our experiments on the constitutive behavior of chondroepiphysis will continue, using a simple linearly viscoelastic approximation of biphasic material behavior developed during the previous year. Axial compression tests of newly ossified trabecular bone specimens are expected to begin early in the upcoming year, as are axial tensions tests of cortical bone specimens from the proximal diaphysis and neck. We plan a series of bench tests to further explore the efficacy of Prescale film as a substitute for piezoresistive transducers for the human contact pressure measurements. Work on developing a semiautomated finite element mesh generating scheme will be continued, to be followed by a dry run of the full three-dimensional stress analysis problem. Intensified efforts will be focused on the problem of obtaining more human autopsy specimens.

By the end of the upcoming year, we hope to be into the early production phase of collecting constitutive data and performance stress analyses on several of these final human specimens■

[See also **II. Orthotics, A. Lower Limb**, Design and Evaluation of a Knee Orthosis; **III. Total Joint Replacement and other Orthopaedic Implants, B. Hip**, Biomechanical Assessment of Patients Treated by Joint Surgery, Quantitative Analysis of the Effect of Total Hip Arthroplasty on Stress and Strain in the Human Pelvis, The Efficacy of Radiolucent Low-Modulus, Total Hip Surface Replacement, and Total Hip Implant Biotelemetry; **C. Knee**, Interaction of Total-Knee Replacement Geometry with Knee Ligaments, Investigation of a Simplified Internal Knee Prosthesis, In Vivo Loading on Total Knee Joints, and Biomechanical Study of Total Knee Replacement]

3. Upper Limb

Functional Forces in Normal and Abnormal Fingers

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This research project will study five problems related to functional forces in normal and abnormal hands: (i) ligament force analysis of finger and thumb MCP joints, (ii) pathologic force simulation investigating tendon, nerve, and joint injuries, (iii) intrinsic muscle distribution, (iv) in vivo tendon testing, and (v) hand patient functional evaluations.

Our specific aim will be to complete analysis of ligament contributions, both theoretical and experimental, to analyze hand joint stability, and to calculate intrinsic muscle force response to static loading. We will validate flexor and extensor tendon forces by in vivo buckle transducer studies. We will then apply our normative model to pathologic hand involvement of nerve, tendon, and joint problems. Finally, we will integrate this information with the clinical setting to obtain a hand function index to evaluate preoperative and postoperative joint arthroplasties, tendon transfers, and ligament reconstructive procedures. Ligament stiffness contributions to MCP joint stability have been initiated and will be completed this year.

The methods involve applying ligament anatomic and strength data to perform an equipollent force analysis to distribute the resultant force among the ligament components and joint articular surfaces. The contact area of the joint surfaces under load will be further studied using cartilage staining techniques. Pathologic force resulting from rheumatoid hand deformities, tendon lacerations, and peripheral nerve injuries will be simulated in our tendon model to predict resultant hand deformities and function loss, and the results compared with in vitro and in vivo studies of subjects with joint subluxations, muscle weakness, and tendon malfunction. Hand functional strength assessment in neuropathic conditions will be completed. In vivo tendon forces will be measured in patients with carpal tunnel syndrome or tendon transfers. With a strain-gauge instrumented pinch meter, the applied finger/thumb force will be compared with directly measured tendon force (buckle transducer). Finally, functional hand evaluations will combine motion, strength, dexterity, and daily activity analysis to establish a Hand Performance Index.

The results will compare a normal subject population with preoperative and postoperative individual patient assessments, and the results will be distributed to clinicians■

Static Force and Stability Analysis of the Human Elbow

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The objectives of this project are: (i) calculation of the muscle and joint forces of the elbow joint under static and dynamic conditons; (ii) verification of the theoretical results by using quantitative electromyographic measurements as well as function strength evaluation; (iii) examination of the role of ligaments and articular surfaces in elbow joint stability; and (iv) biomechanical evaluations of surgical procedures and prosthesis replacement for treatment of the elbow joint.

A normative model of the muscles and ligaments around the elbow joint has been established. This model will be used to calculate the muscle and joint forces under static and dynamic conditions. An optimization method based on newly designed objective criteria will be used for solution of the indeterminate problem. The estimated length and tension relationship of each muscle across the elbow joint will be implemented in the model for muscle force calculation.

Results of quantitative electromyographic (EMG) experiments have been obtained. The application of these EMG data for muscle force calculation will be performed and compared with those of the theoretical calculations. The contribution of ligaments and articulating surfaces to elbow joint stability under static conditions will be studied by using stiffness and laxity tests. Joint contact areas under load will also be examined.

Finally, various designs for joint replacement will be assessed using bench tests as well as patient functional performance■

Biomechanics of the Wrist

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Wrist Kinematics—The objective of this proposal remains the characterization of motion in the rheumatoid wrist and in the surgically reconstructed wrist. We intend to accomplish in the next year these specific aims: (i) complete the statistical comparison of the kinematic variables in three study groups (15 normal wrists, 18 rheumatoid wrists, and 7 postoperative Swanson wrist implants) and (ii) complete the correlation of radiographic indices and kinematic variables in 18 rheumatoid wrists. The motion is determined by the use of a three-dimensional sonic digitizer. Spark gap arrays are secured to the forearm and hand. Orthogonal, oblique radiographs are taken of the extremity with the spark gaps in place. The patient is positioned in the sonic digitizer field and completes a prescribed series of motions. The motion is described by the specification of the location and orientation of the corresponding screw displacement axis (SDA) about which the hand moves relative to the forearm. Radiographic indices are calculated from PA views of the wrist. Indices include carpal height ratios and carpal translation.

Wrist Kinetics—The objective of this proposal remains the measurement of moments, torques, and angles of twist in the total wrist prostheses in cadaveric arms, in normal undiseased wrists, in rheumatoid wrists, and in surgically reconstructed wrists. We intend to accomplish in the next year these specific aims: (i) initiate in humans the measurement of moments in normal, unoperated rheumatoid and surgically reconstructed rheumatoid wrists and (ii) initiate in cadaveric wrists the measure of moments, torques, and angles of twist effected by a commonly used tendon transfer in rheumatoid wrist reconstruction, the ECRL to ECU transfer.

The moments are determined by securely mounting a cadaveric forearm with six transfixing Steinmann pins in an experimental apparatus. Sequentially, the six prime wrist movers are loaded with a 4-kg mass. The induced moments about the wrist are transmitted by a rod mechanically attached to the hand to a configuration of load cells. The resulting load cell's output voltages are recorded. The experimental apparatus is also designed for the in vivo studies, but will require adaption for arm immobolization and rod attachment■

Biomechanical Study of the Radial-Ulnar-Carpal Joint

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During the next year of support, the primary scientific goal of this investigation into the anatomy and function of the radial-ulnar-carpal joint is to continue to measure the forces and pressures on the radius and ulna for intact and surgically modified wrists. The pressures between the distal radius and ulna also will be measured using our current methodology. Cadaveric forearms mounted in a frame will be loaded via the wrist flexors and extensors, with the forces on the radius and ulna being measured by load cells attached to those bones. The pressures at the articulating joints will be recorded on pressure-sensitive film. These force and pressure measurements will show us in vitro the consequences of various surgical procedures for the distal radial-ulnar-carpal joint.

Five surgical procedures will be examined this coming year. In the first two procedures (lengthening and shortening of the ulna and partial excision of the articular disc of the triangular fibrocartilage complex), only the pressures between the distal radius and ulna will be examined, as the radial-ulnar-carpal joint force and pressure measurements will have been completed.

The effects of three other surgical procedures on the force and pressure measurements on both the radial-ulnar-carpal joint and the distal radial-ulnar joint will be examined. These procedures are: (i) carpal ligament divisions (scapholunate, scaphotrapezial-trapezoidal, lunotiquetral), (ii) carpal malalignments (dorsal intercalated segment instability, palmar intercalated segment instability), and (iii) ulnar-carpal translocations. Two additional procedures: carpal excisions (scaphoid, lunate, triquetrum); and, intracarpal fusions (scaphotrapezial-trapezoidal, scascapholunate, lunotriquetral, triquetrohamate) will be started during the following year■

[See also **VI. Biomechanics, D. Upper Limb Function,** Processes Underlying Arm Trajectory Formation]

B. Spine

The Role of Abdominal Muscles in Stabilizing the Spine in Flexion: the Mechanics of Force Transmission

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For many years it has been accepted that the principal function of the thoracolumbar fascia (TLF) has been to form an origin for the muscles of the abdominal wall, and thus to provide a firm anchorage from which they act to compress the abdomen. It has been argued that the resulting increase in intra-abdominal pressure (IAP) can reduce both the bending and axial loads on the vertebral column. In the past decade, the work of Farfan and others has recognized the potential for an additional mechanism by which the TLF may stabilize the lumbar spine. For example, Fairbank and O'Brien demonstrated that when the fascial sheet is subjected to lateral tension it extends the spine. In so doing it will, of necessity, increase the compressive, axial force on the spine. Although they involve the same tissue structures, the two supporting mechanisms outlined above conflict biomechanically. We have investigated this problem by several different methods.

In contrast to the large number of investigations on IAP, very little has been published on the mechanical characteristics of the TLF. Uniaxial and biaxial tensile testing of samples of the posterior layer of the TLF have been carried out in a physiological environment using optical extensometry. Polarizing light microscopy has been employed, in conjunction with a loading device, to quantify the change in structure of the fascia under load.

Whole cadaver studies are underway to measure the sagittal movements of the lumbar spine in a simulated lifting posture—this involves fixed hips and the spine flexed to the point where it is supported solely by the ligamentous structures (similar to in vivo conditions in which it has been shown that the paraspinal muscles are inactive). In this study, three rubber balloons are positioned along the length of the abdominal cavity. The central balloon is constrained internally in an axial direction so that when inflated in isolation it develops tension in the muscles of the abdominal wall alone. When the outer two balloons are also inflated to the same pressure additional forces are developed on the diaphragm and pelvic floor, thus simulating a raised IAP. The central balloon is designed so that it can deflate while leaving the outer balloons acting on the diaphragm and pelvic floor. Thus, the two supportive mechanisms ascribed to tension in the abdominal muscles in vivo can be simulated in isolation and in concert.

Uniaxial tests revealed that the TLF is approximately twice as stiff as has been previously suggested, and constrained biaxial tests yield corresponding results. Combined microscopic and mechanical examination indicate that the net-like structure of the posterior layer of the TLF is not highly mobile. The cadaveric studies displayed similarly high stiffness within the fascial layer, yet its influence on the sagittal movement of the vertebral column was noticeable.

The Detailed Anatomy of the Vertebral Attachments of the Thoracolumbar Fascia and Its Functional Implications

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In 1980 Fairbank and O'Brien suggested that there was an interaction between the thoracolumbar fascia (TLF) and the posterior vertebral ligaments of the lumbar spine. Tension in the TLF due to abdominal muscle action could be transmitted to the ligaments causing them to deviate laterally and thus produce an axial contraction. In this way, abdominal muscle contraction could be converted to tension in the ligaments which will stabilize the lumbar spine (e.g., in lifting maneuvers). In view of the current confusion in the anatomical literature we have made a detailed study of the TLF and its connections that underlie these important biomechanical implications.

Dissections of the lumbar region were made of four fresh and four embalmed cadavers. Special attention

was paid to the posterior layer of the TLF, the junction of the posterior layer with the supraspinous and interspinous ligaments, and the attachments of the middle layer of the fascia to the transverse processes. Computerized tomography (CT) was used on volunteers to clarify the spatial relationship between the TLF and the ligamentous structures in the lumbar spine in standing and flexed positions and during the valsalva maneuver. Conventional histological techniques were used to examine the laminar structure of the posterior layer of the TLF and the attachments of the fascia to the vertebral ligaments and the transverse processes of the vertebrae. The tissue interface between the posterior layer of the TLF and the ligaments was also treated with a modification of Masson's Trichome stain, to identify tissue fibers under tension. This showed the load transmission pathways in the connective tissue components under conditions simulating flexion, abdominal muscle action, and their combination.

The results of these investigations have confirmed and clarified anatomical features previously published. In addition, some new findings were made which could have significant functional implications. The CT scans revealed that, rather than lying in the coronal plane, the posterior layer of the TLF, on leaving the midline, is directed posteriolaterally, even in full flexion. The deep lamina of the posterior layer of the TLF blends with the interspinous ligament in the sagittal plane. Although this attachment does not enable the fascia to pull laterally upon and thus open the bifid interspinous ligament, it may still generate tension in the ligamentous fibers. In addition, the supraspinous ligament may also be put under tension as it is enveloped and pulled posteriorly by the outer two laminae of the fascial layer. The middle layer is attached to the transverse processes of the lumbar vertebrae and the intervening intertransverse ligaments. These ligaments are thin and membranous with no obvious fiber arrangement, and they extend to the base of the transverse processes. In contrast, the attachments to the tips of the transverse processes are thickened and consist of converging fiber bundles. This fiber arrangement is ideally suited to enhance stability in the coronal plane as a result of abdominal muscle action■

Mechanical Analysis of Cervical Spine Stabilization Techniques

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Sponsor: Veterans Administration Rehabilitation Research and Development Service

Little information is currently available about the efficacy of techniques for internal stabilization of the cervical spine. The objective of this study was to develop a methodology for analysis of spinal motion with controlled loading and to apply this methodology to two types of cervical spine stabilization, interspinous wiring and a segmental wiring technique.

Materials and Methods—Four intact human cervical spines (C1 to T1) were obtained from fresh donated cadavers and frozen prior to use. Each spine was stripped of surrounding musculature, but all ligaments and joints were carefully preserved.

For testing, each specimen was thawed to room temperature, and C1 through C3 vertebrae were embedded in resin for mounting. Forces were applied via a 12 cm moment arm to a loading fixture on T1. Utilizing four heavy Steinmann pins, a 6 degrees of freedom motion transducer was affixed to the bodies of C5 and C6. The instrumented spine was mounted on a servohydraulic testing machine (MTS). Analog outputs were fed to a data acquisition and analysis system (HP). Computer programs were written to generate force-displacement curves.

Each spine was tested under loading conditions that produced axial rotation, lateral bending, and flexion-extension as the primary motions. Coupled motions were allowed to occur as they would in vivo.

Following intact testing, a flexion-distraction disruption at C5-C6 (in our experience the most common) was produced by cutting the disc and all ligaments except the anterior longitudinal ligament. The spine was then retested following stabilization with each of two methods: (i) interspinous wiring between C5 and C6, using 20 gauge stainless steel wire; and (ii) segmental stabilization from C4 through C7, achieved by wiring the laminae at each level to a U-shaped 6.4 mm diameter stainless steel rod.

Force displacement data were used to calculate the stiffness at O force (newtons/degree of angular displacement) for each of the primary rotations of the spine in the intact and both disrupted, then stabilized, situations.

Results—Stiffness results are presented in Table 1. Using the student T test, the intact spine was significantly stiffer in axial rotation than in flexion-extension (p=.05) or lateral bending (p=.04); and in lateral bending was significantly stiffer than in flexion-extension (p=.04).

TABLE 1

Rotation	Mean Stiffness N/Deg.		
	Intact	I S Wire	U Rod
Axial	4.8 (1.8)*	2.6 (1.4)	3.0 (1.5)
Flex-Ext.	0.54 (0.16)	2.1 (0.8)	17.0 (17)
Lat. Bend	1.4 (0.41)	0.73 (0.11)	0.60 (0.46)

The disrupted spine fixed with interspinous wiring was significantly stiffer that the intact spine in flexion-extension (p=.02), but significantly less stiff in axial rotation (p=.03) and lateral bending (p=.04). The disrupted spine fixed with segmental wiring was not significantly different in any rotation from the intact spine.

We also looked at the total angular excursion that occurred between +5 newtons and −5 newtons of applied force. These results are presented in Table 2. For the intact spine, displacement was significantly greater in flexion-extension than in axial rotation (p=.03) or lateral bending (p=.02). Differences in excursion between the intact spine and the disrupted, fixed spine (for either type of fixation) were probably not significant for axial rotation and lateral bending. For flexion-extension, the decrease in excursion allowed by the U rod as compared to the intact (one-sixth) was highly significant (p=.001) and the decrease in excursion allowed by interspinous wiring as compared to intact (one-half) was significant (p=.01).

TABLE 2

Rotation	Mean Angular Excursion (+5 N.)		
	Intact	I S Wire	U Rod
Axial	2.5 (1.0)*	3.6 (1.8)	2.8 (1.4)
Flex-Ext.	6.6 (0.9)	3.2 (1.3)	1.1 (0.7)
Lat. Bend	4.1 (0.6)	6.6 (2.4)	5.6 (4.2)

* (standard deviation)

Conclusions

1. Force-displacement behavior of a cervical segment can be determined as described by using a motion transducer and a servohydraulic mechanical testing system.
2. For a flexion-distraction lesion at C5-6 fixed with interspinous wiring, stiffness in flexion-extension is four times that of the intact spine; and in axial rotation and lateral bending, the stiffness is about one-half of that of the intact. With interspinous wiring about one-half the intact flexion-extension is allowed (for +5 newtons applied force).
3. For a flexion-distraction lesion at C5-6 fixed with a segmentally wired U rod, the stiffness in all three rotations is probably no different than the intact spine. However, about one-sixth the intact flexion-extension is allowed (for +5 newtons applied force)■

Biomechanical Study of Spinal Fusion and Its Effect on the Free Segments

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Objectives—The overall objective of this project is to investigate the biomechanics of fusion in the lumbar and thoracic regions of the human spine and its mechanical effect on adjacent free motion segments.

Methods—The methodology to achieve the goals of this study include:

1. Experimental studies to obtain data describing the geometry and load bearing properties of the spinal segments;
2. Development of a mathematical model to adequately simulate the in vivo response of the human spine to physiologic loads; and
3. A parametric study, using the above mathematical model, to elucidate the effects of various fusion parameters on the biomechanics of the adjacent spinal segments.

Experimental Studies—Experimental studies using fresh human cadaver spine specimens have been carried out to obtain data describing the load-deformation properties of lumbar and thoracic spine seg-

ments under axial compressive loads and moments. In order to provide more detailed information on the posterior load path through the facet joints, a series of experiments were performed on single motion segments of the lumbar spine. The contact area, pressure distribution, and load transmitted across the facet joints were quantified using Fuji Prescale pressure-sensitive film for axial compressive loads and extension moments. Further studies are underway using specimens consisting of multiple spinal segments subjected to axial loads as well as torsional moments.

The kinematics of the spinal motion are significantly affected by the motion coupling effect of the facet joints. In order to understand this coupling phenomenon, the three-dimensional geometry of the articulating facet surfaces is being studied. The facet surfaces of each of the thoracic levels (T1 to T12) were mapped using a 3-D digitizer. Each facet surface was then approximated by a plane that is defined with respect to a local reference system via two angles. The pattern of the facet angles gives significant insight into the motion coupling behavior as a function of vertebral level (1 to 12) in the thoracic spine. A similar study is underway to investigate the 3-D orientation of lumbar facet surfaces.

A Three-Dimensional Spine Model—A finite element model of the spine has been developed that incorporates an interactive optimization procedure to identify segmental stiffness properties such that the model's displacement response matches that of the in vivo spine. These response data are taken from pre-corrective and post-corrective X-rays, and the loading imparted by the corrective instrumentation is known.

Each spinal motion segment is modeled as a finite element beam, with end nodes located at the centroids of adjacent vertebral bodies as shown by X-ray. Standard three-dimensional linear elastic beam elements are utilized. However, the model includes geometric nonlinearity due to large displacements. The segmental stiffness properties to be identified are the parameters of the finite element stiffness matrices.

Nodal error functions are calculated based on the difference between the model's displacement and the actual displacement at each node. Any of these nodal error functions can be chosen as the objective function to be minimized, while others (which have been previously minimized) are formed into constraints. Then, using a state-space gradient projection method, the stiffness parameters are altered such that the objective function is reduced without increasing any of the constraint functions. This model is being further refined to facilitate its use in conducting the parametric study mentioned earlier■

Head/Neck/Upper Torso Response to Dynamic Loading

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Sponsor: National Institute of General Medical Sciences

The investigation involves the construction and instrumentation of a replica of a human head, neck, and upper torso, including the skeletal system with rib cage, disks, ligaments, and major muscles. The model also includes the major organ systems of the thorax: heart, lung, and major blood vessel systems.

The model is to be used in vehicular impact studies in which 75 channels of data are to be collected from transducers and gauges placed on the various structural elements and features of the model, including heart, vessels, disks, and muscles. The actual mechanical properties of the various human organ systems will be approximated by using materials with appropriate mechanical properties in the construction of the various model parts.

The investigator also proposes to program a computer model of this system and validate it with data gathered from experiments with the physical model. It is anticipated that the data obtained from these studies will lead to a system for the evaluation of protective devices for the human body■

The Traumatology of the Head and Neck

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The investigator continues to extend his data of the finite element computer model of the human and subhuman primate head and neck. The skull and cervical vertebrae modeling have been completed. The main thrust of this continuing investigation will involve the modeling of the origins and insertions of

head and neck musculature, as well as the attachments of ligamentous elements and intervertebral disks. The finite element model of the subhuman primate will be validated in the laboratory■

The Morphological Changes in the Lumbar Intervertebral Foramina in Normal and Abnormal Motion Segments After Distraction

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Sponsor: University of Strathclyde

The intervertebral foramina of the lumbar spine have been incriminated as potential sources of low back pain. Using a molding technique, an anatomical study of the lumbar intervertebral foramina in human spines was performed to ascertain (i) actual foraminal shape and size with and without distraction, (ii) the effects of intervertebral disc abnormalities upon them, and (iii) the accuracy of various simple radiological measurements. The lumbar foramina were predominantly oval in outline when the disc was normal and auricular when it was abnormal. There were large variations in their minimal cross-sectional area but certain trends were established including the effect of disc degeneration upon them.

The effect of distraction on the foramen was analyzed to ascertain how this influenced any change in foraminal area. Instrument distraction of the neural arches converted the auricular foramen into a more rounded configuration and increased the foraminal area by an average of 20 percent. Small foramina and those in association with abnormal discs showed the greatest increase while those that were large only opened to a minor extent. Excision of the capsules of the facet joints, performed after posterior distraction, did not significantly increase the size of the foramen nor did subsequent anterior distraction. The clinical relevance of this anatomical study suggests that the height and area of the intervertebral foramen may be relevant in some spinal pain syndromes■

C. Human Locomotion and Gait Training

Control of Human Locomotion

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Sponsor: National Institutes of Health
(National Institute of Arthritis, Diabetes, and Digestive and Kidney Diseases)

The contribution of operant conditioning to human locomotion has been a neglected field. The proposed work will continue to study operant (discriminative stimulus) control of muscle electrical activity, EMG, and movements as people walk on a motorized treadmill.

One major aim of the work is to understand cooperation or competition between muscles of different actions or at different joints, when coordination is controlled by public events that are remote from the moving muscles. Separate or co-control that is produced over one or more muscles may reveal possibly obligatory neural or biomechanical machinery. A computer will deliver lights, judge subsequent EMG responses, and deliver a high or low tone after a success or failure, respectively.

A second major aim is to search for presumptive movement-produced stimuli—private events, such as mechanical deformations of tissue that excite proprioceptors or tactile receptors. During the coming year, work that has shown an extensive role for operant conditioning in human motor control will be summarized and extended. Wholesale shifts in rhythmic locomotor patterns will continue to be examined for their implications as to eye-limb coordination. In addition, investigations so far have amply documented the existence of movement-produced stimulation. In the next year, some experiments will attempt to specifically condition such private control.

Results as a whole will help to establish the reflexive or acquired origins of movement to aid (i) understanding of bodily mechanism of rhythm generation and, (ii) learning of movements and/or movement sense by normal or gaitdisordered individuals■

Evaluation of Methods to Measure Locomotion Performance and Activity

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Sponsor: National Institute of Handicapped Research

There are now a number of relatively inexpensive methods for measuring characteristics of gait of individual patients and for assessing the amount of activity carried out by individual patients. Some of these methods are designed primarily for clinical use; others offer new possibilities for evaluating the usefulness of experimental devices and treatment methods.

Among the systems being studied are (i) the Moss Gait Mat, (ii) the use of a 4-channel physiological ambulatory monitoring device that will record the number of steps and heartbeats against time for 24 hours, and (iii) a questionnaire developed by H.B.J. Day, of the Limb Fitting Service in England. Results from these and other methods will be correlated to determine how each or combinations of them can be used efficiently■

Quantitative Interpretation of EMG During Gait

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A major concern in the evaluation of neuromuscular gait disorders is the lack of adequate knowledge about the relationship between EMG signals and actual muscle effort. This currently limits our understanding needed for clinically interpreting dynamic EMG recordings. In most gait EMG analysis, interpretation of the signal is recorded as only whether a muscle under study is ON or OFF; in some, the interpretation of muscle effort is related in some way to the intensity of this ON signal. This classification is straightforward in normal subjects where clear differences between periods of activity and inactivity may be observed with obvious boundaries and large amplitude differences. This is not the case in many gait disorders, i.e., cerebral palsy, where muscles may be active throughout the gait cycle, (with some variation in amplitude) or where there may be several bursts per gait cycle with intervening activity which may or may not be distinguishable from low-amplitude noise and interference. We are seeking to develop a more refined method of interpreting EMG recordings by examining such recordings in a group of subjects with gait disorders and evaluating the major characteristics, in order to obtain a better clinical interpretation of EMG recordings and in order to shed more light on actual muscle effort.

Two approaches to EMG feature extraction are being evaluated for seven major muscles (groups) of the lower limb recorded from surface fine-wire electrodes (gastrocnemius, anterior tibialis, rectus femoris, gluteus maximus, gluteus medius, medial hamstrings, and adductors). The first of the approaches is modeled on the traditional binary subjective classification, and is being implemented as an automated computer determination of the ON/OFF pattern by integrating the absolute value of the full-wave rectified signal with a variety of moving-window-average filters to examine its effect on the discriminated features.

In the second approach, instead of applying a threshold decision to the resulting smoothed data, the Fourier series representation of the EMG envelope is computed with 13 coefficients retained. The statistical methodology of cluster analyses is then applied to this data, in order to determine whether classifications or groupings based on EMG binary (ON/OFF) or Fourier coefficient data can be made. We also will evaluate the effect of going from a binary classification to tertiary or quaternary, etc. (the dynamic range of the signals will be partitioned into 2, 3, 4, or more levels), and time and level data will be used in the classification algorithms. The ability to develop discrete, well-separated clusters in the patient data will be compared for each partitioning level, and the optimal number of levels of coefficient will be determined. The classifications resulting from both EMG processing schemes will be compared with each other, with the classifications from kinematic and force data, and with clinical judgements. On this basis the optimal processing methodology for gait EMG signals is to be selected■

Mechanical Energy Analysis of Abnormal Gait

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We have previously examined the validity of using mechanical measures of work to indicate the metabolic energy consumption during normal gait. These mechanical measures were: (i) mechanical work done on the center of mass per kilogram body mass per second (W cm), calculated by integration of ground reaction forces measured by force platforms; (ii) total body segmental work per kilogram body mass per second (W seg), calculated from individual body segment energies measured by motion analysis; and (iii) the sum of the normalized absolute moment impulses per second acting on the joints of the lower extremities (M), calculated from both force and motion data. The results of this previous work indicate that, for normal gait, there are strong linear relationships between mechanical work or normalized moment impulse per second and energy consumption per second. The linear relationships between these mechanical parameters measured per meter, however, were not as strong.

The work in this granting period has begun to focus on the application of all these facts to energy analyses of pathological gait. In moving toward this objective, our goal has been, first, the examination of elderly patients with degenerative arthritis. We have examined a group of subjects with degenerative arthritis of only one knee and have published these results. Efforts are continuing to examine subjects with multijoint involvement. Examination of such patients in this last year has shown that it is impossible to obtain the metabolic consumption of such patients with accuracy if treadmill walking is used. Such patients have a difficult time maintaining a steady state on a treadmill when paced by the speed of the treadmill, with or without cadence monitoring. As a consequence, to obtain metabolic energy consumption data to compare to mechanical factors of gait, we are currently exploring the use of the Beckman Breath-by-Breath analyzer in such patients walking on the treadmill and walking with free speed on a flat and level ground. This will enable us to determine the variation over time of such measurements, and allow us to obtain either an average or representative time period to compare to single-cycle mechanical energy measurements.

Work also has progressed in the area of refining our mechanical energy processing techniques for routine clinical use. The acquisition of a VICON automation motion system, and the now routine use of four force platforms within the laboratory, provide us with the opportunity of incorporating mechanical energy measurements as part of the routine clinical procedure for all gait studies we perform. This opportunity has required modifying many of our software routines to allow the calculation and graphing of the mechanical energy parameters automatically, much as our motion and EMG data are currently handled. This task is expected to be completed by the end of the present granting year■

Objective Interpretation of Gait Analysis Data

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The goal of this project is to produce a reliable objective method for the clinical interpretation of measured gait parameters obtained in laboratory testing. This includes data obtained from monitoring limb segment motions, EMG activity (muscle effort), and fast-floor ground reaction forces, and the measuring of metabolic (and the calculating of mechanical) energy consumption in association with routine clinical information, i.e., diagnosis, medical treatment, and physical examination.

In this granting period, work has proceeded well in all three aspects (development of a gait typology, data management, and clinical report generation) of this project.

In the past year our efforts have been focused on further examining and refining of the proper feature extraction technique we have utilized for examining time-varying kinematic gait parameters. This technique has involved the use of 13 Fourier coefficients to represent the data. Such coefficients by themselves do not have direct counterparts or physiological representations which can be interpreted easily by clinicians. We have implemented a software program which allows us to reproduce a given time-varying parameter from any one or a number of these coefficients, and are currently examining the possibility of utilizing this technique to determine the clinical meaning of one or a combination of such coefficients. In addition, because various aspects of such time-

varying variables as knee flexion/extension motion can be readily identified (by clinicians knowledgeable about pathological gait) as being important and representing abnormalities, the evaluation of maximums and minimums (with the percent of cycle) in these curves is also being examined. Work to date reveals that both methods may need to be used to properly represent and select features for pattern recognition techniques. However, under what conditions each one is to be utilized is a matter that cannot be predicted at this time.

Data Management—With so many items to be measured, so much data to be obtained per patient, and the need to examine a great many subjects to properly and efficiently achieve our goal of developing an expert clinically applicable gait interpretation system, a sophisticated computer-based data management system is required. This has been recognized from the outset of our proposal. A major amount of the work establishing the data management system was to be performed in this year's (1984) effort.

Various data management schemes and programs already existing have been investigated. We feel that the best approach is to utilize a commercially available system and make software modifications to it to suit the purposes of our research goals. This led to the discovery that the RS1 Data Management System, developed by BBN of Cambridge, seems ideal for our purpose. A key feature of the expert clinical interpretation system we are to develop involves the analyses of time-varying waveforms, sophisticated statistical analyses packages, graphical routines, and recently developed pattern-recognition clustering analyses methods.

We are currently implementing this system's use in our laboratory. These efforts consist of software developments to accomplish the following:

1. The setting up of a file structure for the incorporation of all pertinent clinical information needed to be evaluated in conjunction with gait data. Such information includes patient name, age, sex, physician, diagnosis, subdiagnosis, range of motion of all lower extremity joints, number and type of all ancillary devices, and treatment history by type and time (medication, physical therapy, and all types of surgical procedures);
2. Incorporation of processed gait data (as described above);
3. Graphic routines to output information. This includes both a standard output graphic package comparing differing variables, and the ability, upon request, to alter variables for comparison for particular purposes;
4. The use of statistical packages to evaluate new data and compare it to old data of the same patient (or to similar types of patients) in order to provide an on-line, real-time status report as to how the patient is performing; and
5. The inclusion of mathematical clustering analyses and classification principles to provide patient pattern recognition.

The proper implementation of all these elements is no minor effort. Such a system must incorporate new information about the same patient on subsequent testing, as well as new information from new patients. This must be done in such a way as to assure flexibility in file structuring—in order to be efficient in time and disc storage. To incorporate this feature requires the most up-to-date principles of data management software programming.

Report Generation—The system for report generation is proceeding according to the original plan. At the moment, various methods are being explored. In the first half of this year we have implemented a word processing type of report-generation scheme. This leads the clinician through the interpretation of gait data (an interactive step-by-step process) to assure that all data are examined and interpretation of each measurement is made. Its use has been tested on physical therapists and physicians who have had only the standard presentation of kinesiology as part of their P.T. or medical school courses. Utilizing only the graphic output and written data of a patient, we have tested this system and have been able to reduce the training period of such individuals from 6–9 months to 6 weeks.

However, we have found the major problem encountered with such a system is still that it fails to allow such individuals the opportunity to properly weigh the importance of each measurement, and to incorporate clinical information in the process of drawing proper conclusions about patient status or the efficacy of past and future treatments. This was not an unexpected finding. It reinforces our belief in the need to develop a pattern recognition system, thereby producing a functional performance index. It also has assisted us in determining which aspect of this pattern recognition system needs emphasis and refinement—and what the significant limitations in such a pattern recognition scheme are.

Within the next several months there is to be one major publication related to our development of a gait typology for ambulatory children with cerebral palsy■

Studies of Normal and Abnormal Motion

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During the period from July 1, 1983, to June 30, 1984, the Kinesiology Research Laboratory continued its investigations of functional performance of normal persons and of patients with a variety of physical disabilities. The latter part of this period was saddened by the death of Dr. M. Patricia Murray.

The first of two studies published during this period dealt with the gait patterns of seven above-knee amputees who were tested using prostheses with constant-friction knee components and using hydraulic swing-control knee components. Their multiple displacement patterns, stride dimensions, and temporal components were measured during slow, free-speed, and fast walking. Gait with the hydraulic-type prostheses was improved over gait with the constant-friction type. With the hydraulic component, the amputees had a wider range of walking speeds, the durations of the stance phases on the prosthetic and sound limb showed less inequality, and forward motion was smoother. Several improvements toward normal were also seen in the displacement patterns of the prosthetic limb during walking with the hydraulic component, including the patterns of knee flexion-extension and vertical displacement of the heel and toe on the prosthetic side.

Despite gait improvements with the hydraulic component, many abnormalities were retained that were present with the constant-friction component. These included inequality in successive swing phases, excessive lateral lurching toward the prosthetic side during prosthetic single-limb support, and vaulting during sound single-limb support. Some of these abnormalities may be habit patterns and others may be necessary compensatory maneuvers for an above-knee amputee.

A second study continued our series of investigations of patients with total hip joint replacements. The purpose of this study was to do objective kinesiologic testing of a group of patients before and after revision of total hip replacements due to noninfectious loosening. Baseline data to identify which components of function decline with loosening (and to what degree), and to identify which components of function improve after revision, were provided by a control group with uncomplicated primary total hip arthroplasties.

There were 31 primary total hip replacements and 31 total hip revisions. Measurements of functional performance were made before surgery and 6 months afterward. Data collected included: range of motion of the hip, strength of hip abductor and adductor muscles during maximum isometric contractions, weight distribution between the feet during standing, forces applied to canes or crutches during walking, and multiple simultaneous displacement patterns during free-speed and fast walking. Each patient also answered a questionnaire about pain and performance of daily activities.

As a result of primary total hip replacement, patients in the control group regained a significant amount of function (in the absence of postoperative complications), but they did not reach normal levels of function. As a result of loosening of the prosthetic components, functional abilities of the patient declined to levels approximately the same as before the primary surgery, with a few exceptions. Loss of motion into hip flexion and extension, decrease of hip adductor muscle strength, and decrease in the use of hip flexion-extension during walking were not as severe in those with loosening as in those with coxarthrosis prior to initial total hip replacement.

After replacement of the loose prosthetic components, function in the patient returned to levels approximating those found after primary total hip replacement. Patients with revision, however, tended to have a greater reliance on assistive devices after surgery than those in the control group. A 2-year follow-up of these same patients is in progress.

In addition, work is nearly completed on two studies of normal function. The first is a study of the kinematics and electromyography of slow, free, and fast walking and the second is a study of strength of the knee flexor and extensor muscles of women 20 to 85 years of age■

A Self-Contained Portable Force and Movement Measurement System to Aid Diagnosis and Rehabilitation of Human Movement Disorders

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Sponsor: National Institute of Handicapped Research

The work described here is a continuation of an effort which started with the specific aim of improving above-knee amputee gait training through development of instrumentation for measurement of gait parameters and biofeedback of gait parameters. As prototype hardware was completed, its general applicability became apparent. Although the immediate focus of the effort remains on above-knee gait training, the criteria that guide design decisions are more global. A self-contained, portable, force and movement meaurement system has many applications in diagnosis and rehabilitation.

The gait training aid (Strider) is a microcomputer-based instrument that has been programmed to provide the following:

1. Threshold and/or proportional audio biofeedback of the prosthesis weightbearing (is the proper weight being applied to the prosthesis?).
2. Average peak weightbearing during a series of steps.
3. Percentage of stance cycles when the adjustable weightbearing threshold was attained.
4. Threshold and/or proportional audio biofeedback of hip extension angle (is the person standing erect during stance?).
5. Percentages of cycles when the hip extension threshold was exceeded during stance.

During the past year, several subtle changes have been made in the instrument's software, but the main effort has been directed toward improved force and movement transducers.

For a weightbearing transducer to be clinically acceptable, it must be compatible with existing post-operative prostheses and training procedures. Such a transducer has been designed and built. It uses a thin cylinder of elastomer to isolate the axial load on the prosthesis from the large bending moments which occur in the shank. This allows a strain gauge to measure one type of loading without being substantially affected by large stresses in other directions.

New Movement Transducer

The movement transducer also has changed dramatically. The new system is essentially a radio direction finder. A small transmitting antenna is placed on one body segment and a crossed pair of receiving antennae are placed on another body segment. Appropriate processing of the signals from the two receiving antennae yields a very well-behaved indication of the angle between the transmitter and receiver. A clinically rugged version of the transmitter/receiver system has been built.

The Strider has been used and evaluated by the physical therapy staff at the Massachusetts General Hospital. The therapists' reaction was enthusiastic. The system looked good and performed consistently and reliably, doing what it was designed to do. It seems to enhance learning at some points in the amputee's training.

As a result of clinical testing, improvements to the system are being considered. Most of them involve increasing the flexibility and the ease of use of device. Particular concerns are allowing the therapist more flexibility in changing the threshold values, providing more alternative forms of biofeedback, eliminating wires, and reducing the weight of the portions of the system worn by the patient.

Locomotion: Idling Metabolism and Gait Dynamics

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Sponsor: National Institutes of Health
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The long-term goals reflected in this proposal are:

1. To determine the manner in which muscles and populations of fibers within muscles are recruited during locomotion; and
2. To investigate the relationship between muscular activity and muscular-metabolism.

In previous work, we have described the spatial recruitment patterns that occur within and among mammalian muscles during exercise. Also, we recently have found that the magnitude and distribution patterns of blood flow within and among muscles of rats vary with the fiber type composition of the muscles and with locomotory speed, and that muscle blood flow increases with time during exercise to fatigue at a constant speed. We have concluded from this work that muscle blood flow patterns are closely related to muscle fiber-recruitment patterns.

Two immediate questions emanate from our previous work:

1. Are the absolute magnitudes and the patterns of blood flow observed within and among the rat muscles representative of other mammals, or are they unique to laboratory rodents?

2. Are progressive changes in muscle fiber recruitment responsible for the gradual elevations in muscle blood flow that occur over time during exercise, or are other mechanisms involved?

To answer the first of these questions, blood flow within and among the muscles of pigs and dogs will be determined during exercise. To answer the second, we will test three hypotheses that may explain the progressive increases in muscle blood flow that occur with time during exercise: (i) the elevations result from progressive recruitment of additional motor units in the muscles as fibers fatigue, (ii) the elevations result from a progressive rise in body temperature, or (iii) the elevations result from progressive accumulation of vasodilator substance in the muscles. Answers to these questions will significantly further our understanding of the patterns of muscle fiber activity that occur during exercise and the accompanying metabolic support of the muscular activity■

Medical Gastrocnemius Muscle Function in Locomotion

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Sponsor: National Institutes of Health
(National Institute of Arthritis, Diabetes, and Digestive and Kidney Diseases)

The specific hypothesis that central nervous system control of locomotion is focused on distinct parts of individual muscles rather than on whole muscles or synergistic groups will be tested. The activity of single motor units in distinct parts of the triceps surae muscle group of cats during a broad range of stepping behaviors will be recorded. Each motor unit recorded will be carefully characterized using physiological criteria, and its location in the muscle examined by glycogen depletion and histochemical analysis. The pattern of recruitment of motor units in each part of each of the muscles will be correlated with the physiological properties of those units. These patterns will then be compared in different parts of the muscle to determine if motor units are recruited with any level of independence in different parts of the same muscle.

The results of this study are expected to be significant in establishing guidelines for studies of the mechanisms and the specificity of motor control during behavior. They also should be of use to clinicians, especially in neurology and rehabilitation medicine, in the diagnosis, treatment, and evaluation of patients with disorders of movement, especially those involving the locomotor apparatus■

Development of a Clinically Applicable Model of a Gait

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Analysis of the influence of the states and controls can be an important tool in the evaluation of pathological gait. It is well known, clinically, that alterations in one part of the leg, i.e., a tendon transfer or muscle release around the ankle, produce changes in the kinematics of all limb segments. The analysis of the influence of the states and controls provides a means for explaining the propagation of a localized change throughout the system. More importantly, it may be useful in aiding the identification of those areas where clinical interventions would be most beneficial. For example, if the shank acceleration is too low, so that the knee cannot come to full extension at heel strike, we would determine which variables had positive and negative influences on shank acceleration. Consideration would be given to those clinical treatments that had a net positive effect on the shank acceleration.

In the coming year we are planning to:

1. Apply the three-dimensional model to evaluate the primary changes in a pathological gait following a surgical procedure;

2. Quantitatively evaluate the effects of mass and mass distribution in prostheses for above-knee amputees with the intent of developing design criteria;

3. Complete the measurement of the results of the effect of the passive elastic moment at the knee and evaluate the effect of hip and knee passive moment during gait■

Feature Extraction for EMG Gait Analysis

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Introduction—Objective gait assessment is recognized as a necessary component in evaluating locomotor disabilities. Computerized evaluation of electromyographic (EMG) data is one component of this assessment. Essential to computerized EMG evaluation is the extraction of important waveform features that are easily understood and amenable to further analysis. Since the linear envelope is the accepted modality for describing the EMG waveform in gait, a good feature extractor would indicate the times and intensities of phases of EMG activity.

Methodology—A method that will extract the times and intensities of EMG activity phases is the Tauberian approximation shown in equation (1) below

$$y(t) = \sum_{i=1}^{M} a_i x(t-\tau_i) \qquad (1)$$

where y(t) is the approximation of the EMG envelope over one stride; x(t) is a basis function; τ_i is the time when some activity occurs; a_i is the intensity of that phase of activity; and M is equal to the number of phases. The features are a_i and t_i. When considering the linear envelope on the normalized time scale, that is, time between 0 and 100 percent of a stride, a very suitable basis function is the Gaussian function

$$x(t) = \exp[-t^2/2\sigma^2] \; |t| \leq 2/4\sigma \qquad (2)$$

with σ having a range between .04 and .08. Features are calculated through equation 3

$$H(w) = \frac{Y(w)}{X(w)} = \sum_{i=1} a_i \exp[-j\tau_i w] \qquad (3)$$

This equation is solved by using the discrete Fourier transforms of the average EMG envelope, Y(w), and basis function, X(w), to produce H(w), and then using the Prony method to calculate the a_i and τ_i. (Note that the scale factor for x(t) is incorporated into a_i, giving x(t) a peak value of 1.0).

Results—In an approximation of tibialis anterior muscle EMG of a normal female walking at 0.97 meters per second with a stride time of 1.1 second, the time scale is percent of stride and the waveform has been normalized to have an average of 1.0. Five terms were used and the features are listed in Table I. The technique extracts the phase of activity during early stance, the longer duration phase during the stance-to-swing transition, and the phase of activity during late swing. Notice that small intensity activity is used to complete the monophasic burst during early stance.

TABLE 1.

EMG Envelope Features

Time	Amplitude
6.1	2.34
16.1	0.44
70.9	2.47
80.1	2.59
94.7	1.52

This approximation was attempted on five different leg muscles in five normal individuals walking at various speeds. There was good correspondence in II approximations. Two parameters are vitally important when using this technique. These are the number of terms, M, and the duration of the basis function, σ. These parameters are easily adjusted with automation to produce a good approximation■

D. Upper Limb Function

Processes Underlying Arm Trajectory Formation

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A series of experiments has been outlined that involve kinematic observations made under a variety of conditions in animals, normal subjects, and patients affected by a sensory neuropathy. In parallel with these kinematic observations, we are proposing a computer simulation research directed at defining one possible control strategy subserving the formation of arm trajectories. The idea underlying the simulation work is the potential valley concept, which derives from spring-like muscle properties.

The following experiments are proposed:

1. Alteration of Biomechanical Structure. We plan to study the kinematic role of those muscles that span two joints. In conjunction with this study, we also will analyze the electrical activity of the two-joint muscles and compare it with the one-joint muscles.
2. Studies of Patients with Sensory Losses. Kinematic studies will be performed in patients affected by a neuropathy of unknown origin that totally or partially deprives these subjects of joint position sense, cutaneous sensations, and proprioceptive feedback from muscles.
3. Deafferentation of Monkeys. Depending upon the outcome of the patients' study, the question of the role of proprioceptive feedback during trajectory formation will be studied in monkeys.
4. Velocity-Profile Invariance under Gravity Loading. In these studies, we will utilize normal subjects and perform three-dimensional recordings with the Selspot.
5. Alteration of Segmental Parameters. Again with the Selspot, we will see how kinematic patterns of the arm are changed when masses are attached to the arm and rods are attached to the hand.
6. Arm Movements under Orientation Constraints. We propose to contrast movements executed under hand orientation constraints with those performed without such constraints to learn whether the extra kinematic complexity is manifested through different types of trajectories.
7. Simulation of Movement. We will focus on evaluating the implementation of the potential energy valley idea, particularly the way in which this hypothesis might allow the formation of trajectories with realistic kinematic features.

It should be stressed that both the biological studies and the simulation of work derive, at least in part, from the assumption that muscle spring-like properties and factors intrinsic to the biomechanical structure of the arm may be used by the controller to form arm trajectories. The simulation model will be tested by applying some of the same broad class of disturbances in the simulation as were applied in the biological experiments above.

E. Other

Bone In Vivo and In Vitro Stress and Strain Patterns

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Bone can adapt to mechanical stress. In recent years there has been a renewed interest in the mechanisms by which bone responds to disuse and to overuse. Disuse changes associated with immobilization, paralysis, and weightlessness and overuse changes associated with repetitive loading during activity have received particular attention. Many studies have been published on the mechanical properties of cortical bone, but few have examined the variation of properties in the growing animal. The purpose of this study is to characterize bone growth (changes in geometric, biochemical, and biomechanical properties) in the maturing animal. The effects of hypokinesia, hyperkinesia, and diet-induced bone disease are being examined.

In previous studies the geometric, structural, and material properties of growing rats were reported. Bone cross-sectional geometry was determined using a computerized numerical procedure. In vitro structural and material properties were determined from both elastic non-failure, and failure bending and torsion tests; in vivo strains were recorded during gait using a technique developed in our laboratories. During growth, the geometric, structural, and material properties increased rapidly until maturity. These increases were best represented by a power curve fit of the data. Comparison of the properties of stressed and non-stressed (voluntary) exercised animals with

the results revealed that intensive exercise produced significant ($P<0.01$) bone hypotrophy (e.g., decreased cross-sectional growth rate, decrease in bone length) as well as significant reduction in structural and material properties. These results question the prevailing belief that exercise is always beneficial. In addition, the data suggest that immature bone maintains or increases material integrity in response to an optimum stress range. Stresses above or below this range have a negative effect on bone material.

Currently, we are investigating the response of bone during disuse. A hind limb suspended and unloaded hypokinetic rat model is being used to examine the biochemical and biomechanial properties of maturing rats. This study will provide information valuable to basic biology, space biology, and the clinician by giving insight into the role of gravity and mechanical stress on the control and functional adaptation of bone characteristics. These data will aid in the development of proper treatment strategies to prevent or minimize bone changes associated with disuse.

Future studies will be directed toward examination of the effects of diet-induced bone diseases (osteoporosis, osteomalacia, and osteolathyrism) on bone properties. In addition, in vitro torsion, bending, and fatigue studies will be performed on immature primate cortical bone. Subsequent comparison of growing rat and primate cortical bone biochemical and biomechanical properties will provide additional insight into modeling (cell activation → osteoblastic formation) and remodeling (cell activation → osteoblastic resortion → osteoblastic formation) processes, respectively. Formulation of a theoretical growth model for modeling and remodeling bone may then be possible. Such a model may allow us to predict the behavior of bone in long-term hypokinetic (disuse, microgravity) and hyperkinetic conditions. Extrapolations of these data to humans under similar conditions also may be possible■

Human Response and Lower Extremity Injury

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The mechanics of human injury is a complex process. External forces are transmitted to the human musculoskeletal system; the system responds in the manner of displacements and rotations. Stresses are induced in the tissues and under some conditions the tissues are disrupted. When the forces are not constant, prediction of the likelihood of injury and the severity of the forces is difficult.

This proposal presents a research program investigating the mechanics of lower extremity injury, specifically injuries to the knee, tibia, and ankle that typically occur in snow skiing. Snow skiing is studied because (i) the lower extremity injury rate is high, (ii) the forces transmitted to the foot can be measured, (iii) response of the lower extremity can be measured, and (iv) safety devices can reduce the high rate of injuries. Specialized laboratory and field test equipment have been developed to measure and analyze the forces between the boot and the ski; the rotations occurring at the ankle, knee, and pelvis; and the integrated EMG from muscle groups during skiing and especially during falling, when severe loading occurs and the likelihood of injury increases. The field measurements identify the injury environment, and the laboratory experiments clarify how the lower extremity responds to dynamic loading. This is the identification problem for the lower extremity.

The true severity of the typical skiing environment and the contributions of the musculature to influence the likelihood of injury will be clarified. The common misconception that the forces of skiing are compared to typical tibia fracture strength and knee ligament strength will be corrected. The erroneous concept is widespread, extending to standards organizations, the industry, and the public alike. The error has major impact on the design of safety devices, on the evaluation and acceptance of safety devices, and on the training and instruction given the public. Efforts are directed to development of meaningful standards of safety■

Foot Interface Pressure Study

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Peripheral neuropathy associated with diseases such as diabetes mellitus often causes severe deficiency in transmission of sensory modalities in the lower extremities. Such losses impair the protective mechanisms and render the extremities vulnerable to the effects of applied forces of daily ambulatory

activity. This not only results in skin ulcerations, but also may cause hyperemia and inflammation secondary to trauma. Many diabetic patients with foot ulcers are seen at the VA Medical Center, and often there is difficulty in achieving healing because means to reduce repetitive plantar pressure are inadequate. Required are criteria for prescribing interface materials and means for evaluating effectiveness of materials chosen.

Hypotheses

The hypotheses in this study are the following:

1. Plantar pressure ulcers in hypo or insensitive feet may be effectively treated by use of appropriate interface materials.
2. Physical properties appropriate for the selection of interface materials can be determined.
3. Adequacy of static load distribution properties of an interface material can be determined by use of a barograph.

Methodology

Clinical Testing—Both diabetic and non-diabetic patients at the VAMC with established findings of peripheral neuropathy are seen periodically to monitor condition of the insole and, for those with ulcerations of the plantar surface, to measure and record the width, breadth, and depth of the ulcer. Patients' weight and ambulatory habits are noted, and the thickness of the used insoles are measured at points of maximum compression set. If the thickness is 50 percent or less of the original thickness, the insole is collected and a new one issued. Thickness of the collected insole is monitored for a week to note any recovery. As a result of static load testing in the laboratory, four pairs of insoles are issued to permit daily changes allowing a 4-day interval for partial recovery in thickness and restoration of cushioning properties. During the initial phase, medium density Plastazote was used with over 50 patients. Recently, Aliplast 4E was introduced to obtain comparative performance results.

Laboratory Testing—Both time-related and non-time-related properties of a variety of commercially available, so-called closed-cell, cellular plastic materials have been preliminarily evaluated. Time-related testing consists of statically loading samples to note changes in thickness as a function of time. After a few days the thickness stabilizes, then the load is removed and the rate of recovery is noted. The slow compression takes place because the closed cells are not impermeable, but allow gases to escape from the cells. Potential energy, stored in the deformed plastic matrix, causes air to be drawn back into the cells when the material is unloaded. Static testing has been done with loads representing 10, 20, and 30 psi.

Non-time-related properties have been evaluated using a manually operated, mechanical X-Y recorder. Samples are loaded and unloaded at rates resembling those during walking. The relation of thickness to pressure is approximated by the following general form:

$$t = t_0 \left[(1-t)\, e^{-ap} + r \right]$$

where t = thickness
t_0 = unloaded thickness
r = compressibility factor
a = compliance factor
p = applied load

The compressibility factor is a ratio tp/t_0, where tp is the plateau thickness at high pressure, usually in excess of 70 psi. Both the compressibility and compliance factors are independent properties of different materials. The shape of the curve depicting the thickness-pressure relation resembles the gas law relation $PV^n = C$ because a part of the work done on the cellular material during compression is stored as potential energy in the gases contained within the cells.

Plans for the Future—Continue the collection of data from the clinical application of different interface materials and different configurations of insoles for relative effectiveness in protecting the plantar area, for durability, and for factors unifying the weight of a patient, contour of the foot, ambulatory activity level, and footwear design. Continue seeking footwear design appropriate for this category of patient. Continue to explore means to locally reduce normal and shear forces in areas of plantar ulcers and to evaluate the efficacy of such means.

[See also **III. Total Joint Replacement and other Orthopaedic Implants, A. General**, Biomechanics of Bone Resorption/Regeneration of the Bone-Implant Interface; and, **V. Functional Assessment**, Quantification of Motor Performance: Muscle Strength and Endurance Testing]