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VI. Biomechanics

A. Joint Studies

1. General

Vibration Studies of Bones and Joints

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Sponsor: VA Rehabilitation Research and Development Service

Purpose — The objective of the two research projects underway is to develop techniques for early diagnosis of joint and bone disorders by studying their vibration characteristics.

Progress — The proposed protocol will characterize vibration analysis including system identification techniques. The following two studies will be performed and correlated:

1) *Knee joint study*. The testing procedure will consist essentially of measuring the acceleration and acoustic emission output from knee joints while they are in active articulation. The tests will be carried out on a sufficiently large number of subjects representing a wide variety of possible joint conditions, e.g., normal, rheumatoid arthritis, degenerative joint disease, etc. Moreover, joint conditions in different stages of severity will be studied. The data will then be processed to evaluate the sensitivity of the technique to the extent or severity of the condition and the sensitivity of the measuring technique to different types of joint abnormality. The equipment and the measuring technique also will be evaluated for convenience in the event of general clinical application. The effect of age, weight, sex, and any other relevant parameters will be examined.

2) *Bone vibration study*. The first part will be to obtain the natural frequencies, damping, and mode shapes of bones *in vitro* by using different methods of excitation, such as hammer impact or shaker excitation. The second part will consist of using these measurements as inputs to an analytical structural dynamic system identification procedure to obtain distributions of physical properties of the bone, such as mass, damping, and stiffness. The *in vitro* measurements will be verified against actual measured properties. If the *in vitro* tests prove successful the *in vivo* test procedure will be developed. Preliminary *in vivo* tests have been done and they are noninvasive and non-traumatic. Sensitivity to the type and severity of the bone disease will be evaluated.

Preliminary Results — During the first 30 days of this project, the investigators assembled the equipment necessary for the proposed work.

Control of Metrical and Timing Precision in Human Movement

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Sponsor: National Institutes of Health

Purpose—This study proposes to investigate central nervous system control strategies used to produce accurate movements. Control of voluntary movement is viewed in this study as a stratified process with several levels of control: 1) movements are initiated by high level construction of open-loop motor commands, which are 2) executed from a reference frame stabilized by a postural control system, and are 3) modified by sensory feedback during both command execution ("concurrent feedback") and after movement completion using knowledge of results ("delayed feedback"). Skilled movements and isometric force production are evaluated in terms of these three control mechanisms.

Progress—Adult, human subjects will track various waveforms presented on a visual display by exerting force on a manipulandum with their elbow musculature. Comparison will be made of motor accuracy under a variety of conditions affecting: 1) the predictability of the stimulus (tracking waveform) amplitude; 2) the availability of visual feedback; 3) the degree of postural stability; and 4) movement of the elbow joint. In most experiments subjects will track step waveforms on an oscilloscope screen while, in one experiment, designed to distinguish between strategies subserving timing and metrical movement precision, graphical displays will be more complex. Electromyographic activity will be recorded from appropriate muscles during tracking experiments in order to characterize movement strategies at a level of peripheral neural commands to muscles.

Amputees fitted with myoelectrically controlled arm prostheses will be used in several phases of this study. In one experiment, these individuals will be used as a model of the "deafferented arm" in order to characterize this role of peripheral somesthetic feedback in the control of accurate movements in normal subjects. In addition, a pilot experiment is proposed which directly addresses the problem of user control of multiple degree-of-freedom powered arms. It is hoped that the latter experiment will lead to the development of a large-scale research and training program for amputees at Good Samaritan Hospital and Medical Center.

Biomechanics of Bone Resorption/Regeneration at a Bone Implant Interface

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Sponsor: VA Rehabilitation Research and Development Service

Purpose—The objective of this work is to clarify understanding of bone remodeling in relation to the biomechanical conditions at an implant-bone interface as a step toward quantitation of "Wolff's Law" as it pertains to implants. Research will attack the problem with the aid of a model involving both trabecular and cortical bone of dogs. Via specially shaped stress devices and controlled application of loads, interfacial bone will be subjected to known states of stress for a one-week-period, to be followed by analysis of interfacial bone activity in response to the dynamic mechanical environment.

Progress—The stress devices (which resemble screw-type dental implants) are implanted into trabecular bone of dog mandibles, and cortical bone of dog radii,

and remain load free for 3 months. Programmed loads then are applied to the stress devices by a computer controlled loading device, and interfacila mechanics calculated by finite element stress analyses. Bone activity is documented by tetracycline labeling and related histomorphometry.

Preliminary Results — Loading regimes have been completed on six loaded and six control screw implants in beagle radii as well as on six T-shaped mandibular implants in six other dogs. Undecalcified bone sectioning has been completed on all tissue specimens and histomorphometric analysis of results is currently in progress using both normal light as well as fluorochrome techniques. Results are to be completed within the final year. Three-D finite element analysis of stress on the implants has highlighted interfacial bonding as a major factor in stress prediction but further work will be required to define the status of this factor in our experimental model.

Stimulation of Repair of Cortical Bone Transplants by Implantation of Piezoelectric Materials: Development Study

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Sponsor: VA Rehabilitation Research and Development Service

Purpose — Our purpose is to develop a new approach to electrical stimulation of bone healing based on design of a less-rigid internal fixation plate incorporating a piezoelectric material to generate electric currents during physiologic loading. We are evaluating two approaches to design of internal fixation plates incorporating piezoelectric materials. In Type I, a piezoelectric ceramic or polymer is attached to the underside of the plate and is in direct contact with bone. In Type II, a piezoelectric ceramic is sealed within the plate; the current output is delivered to bone by electrodes.

Progress — Tests have been conducted with both designs using miniature piezoelectric internal fixation plates ($36 \times 6 \times 1.5$ mm) attached to beagle radius, ulna and femur. Effects of the Type I plates have been studied by histological observations on drill holes or osteotomies beneath the active piezoelectric surface. Type II plates have been studied by measuring output during *in vitro* loading, and during actual walking *in vivo* using beagles. Output also has been measured during excitation with external ultrasound.

Tests of Type I plates have failed to demonstrate any direct action of piezoelectric materials on bone formation. Tests with Type II plates have been successful in generating significant currents *in vivo*. In beagles, following rectification of plate output, average direct currents of 0.2-0.4uA have been generated during walking and currents exceeding 50uA have been generated by external ultrasonic energy (10mw/cm^2) applied to the skin.

Tests of piezoelectrically generated currents on bone formation in rabbits are in progress as are design studies on larger (human scale, Type II) piezoelectric plates for tests in large animals. This new type of orthopaedic implant could add an important resource in prevention and treatment of non-union.

A. Joint Studies

2. Lower Limb

Clinical Biomechanics of the Knee-Rotatory Laxities

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Sponsor: National Institutes of Health

Progress — Much controversy exists over the significance of the knee laxity exam. This has resulted, in part, from a lack of knowledge of the restraining functions of the various ligaments and capsular structures. During the first grant period, we measured the ligament restraints to the so-called "straight instabilities." These instabilities are the anterior-posterior drawer and the straight medial-lateral opening. In the proposed renewal period, we will study the restraining action of the ligaments to the rotatory instabilities. These instabilities involve combined rotational and translational knee motion. The rotary motion is associated with axial tibial rotation. The translations are anterior-posterior drawer and medial-lateral shifting of the tibia.

Future Plans — We propose to address the problem of defining the significance of rotatory laxities with regard to injury by applying three distinct methodologies. They include: 1) measuring the three-dimensional restraining forces of the ligaments to well defined and reproducible rotations of the tibia; 2) measuring the three-dimensional motions which occur during the various clinical exams for rotatory instability along with the changes in motion associated with specific ligament injuries; and 3) synthesizing these results on ligament function into a mathematical model capable of testing our understanding of both the effects of the various individual factors (i.e., ligaments, joint geometry, compressive forces, etc.) and their complex interactions.

Biomechanics of Anterior Cruciate Repairs (Human)

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Sponsor: National Institutes of Health

Purpose — The goal of the proposed research is to better understand the mechanical factors in surgical repair procedures for chronic anterolateral insufficiency of the knee, for which the repair requires an anterior cruciate substitute. Experiments will be run on cadaver knee specimens in which ligament forces will be measured by buckle force transducers on the four major knee ligaments. A six degree-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 3-D 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.

Biomechanical Comparison of Total Elbow Replacement Prostheses

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Sponsor: VA Rehabilitation Research and Development Service

Progress — Mechanical design parameters of nine total elbow prostheses (Coonrad II, Pritchard Mark II, Stanmore, Schlein, Triaxial, Mayo, Capitello-Condylar, London, and Wadsworth) have been compared. All implants were "regular" or "medium" sizes. Eight different biomechanical parameters were measured. After studying cadaver specimens, a geometric relationship was identified to assess the ability of each prosthesis to replicate the flexion/extension center of rotation of the normal elbow.

Preliminary Results — A surprisingly wide range of biomechanical parameter limit values were found among the prostheses: (in degrees) flexion: 124 to 180; hyperextension: 0 to 165; internal/external rotation: 0 to 11.8; cubital angle: 0 to 27; varus/valgus: 0 to 11.5; and (in mm) subluxation 0 to 5.6 (for constrained designs), humeral stem length, 68 to 181, ulnar stem length, 24 to 83. The center of rotation offset ranged from less than 1.5 mm to more than 4 mm.

The Stanmore prosthesis was the most constrained design, the Wadsworth provided no cubital angle, and the Mayo and Coonrad II allowed much greater hyperextension than other designs. This relative lack of mechanical constraint in hyperextension might be a problem in patients deficient in ligamentous constraints. The unconstrained designs typically had shorter stems and surface geometries allowing less varus/valgus motion than all the more constrained designs except the Stanmore. These results were submitted in June 1984 to the Orthopedic Research Society and were presented at the annual meeting in January 1985 (*Transactions of the Orthopedic Research Society* 10:100, 1985).

Clinical failure rates due to loosening, and the wide range of design configurations available indicate that a basic general design envelope for elbow prostheses has not yet been established. The available prostheses are either quite unconstrained to prevent loosening and therefore are limited in application, or are substantially constrained and subject to early failure due to forces transmitted from the constraints to the prosthesis/bone interface. To complete this project, a prototype for a new prosthesis was designed, fabricated and subjected to preliminary mechanical evaluation. The principal goal for the prototype was to provide a moderately constrained (and therefore widely applicable) design which would be much less likely to loosen.

Mechanical analysis suggests that both axial and torsional loads at the humeral interface contribute to loosening of constrained designs. In order to minimize these loads, the prototype humeral component was designed with a titanium alloy stem of cylindrical cross-section free to move axially and rotationally in a close-fitting cylindrical hole centered in a polymer sleeve. The external surface of the polymer sleeve was designed to conform to the shape of the humeral canal with

minimal reaming, allowing cementless, press-fit implantation. The polymer sleeve surface geometry was based on sectioning and measurement of 15 middle-age adult cadaver specimens. The sleeve was fabricated from acetal homopolymer to minimize creep and wear. An acetal bushing also was incorporated into the design of the moderately constrained interface between the humeral and ulnar components. The ulnar component was also designed in titanium with a polyethylene-finned peg providing cementless fixation in ulnar trabecular bone.

The prototype prosthetic components were implanted in cadaver specimens. Radiographic evaluation of humeral intramedullary fit was good. Strain gauges placed on the humeral surface near the internal locations of the titanium alloy stem tip did not reveal any marked dicontinuities in bone strain when bending loads were applied to the humerus. Most significantly, simple elbow flexion produced readily visible relative torsional motion between the humeral component's titanium stem and polymer sleeve, suggesting that the design concept may be effective in reducing forces at the prosthesis/bone interface which contribute to loosening.

A detailed description of this work has been published as a Master of Science Thesis (J.C. Serbousek, *Biomechanical Evaluation of Current Elbow Prostheses and Description of a New Design,* Bioengineering Department, University of Utah, June 1985), and manuscripts for journal publication are in preparation.

Mechanical Function of the Repaired Meniscus

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Sponsor: VA Rehabilitation Research and Development Service

Purpose — Healing of load-bearing tissue does not necessarily constitute restoration of mechanical function, especially if tissue dimensions or mechanical properties change during healing. The objective of this project is to determine the mechanical function of the injured and repaired meniscus, using the healthy, mature canine stifle joint as a model. The canine menisci have been demonstrated to function similarly to human knee menisci and have a similar vascular supply.

Progress — Forty 23-27 kg mongrel canines have received either a complete transsection or a longitudinal incision unilaterally in the medial meniscus, followed in each case by a standard surgical repair. Six additional animals have been subjected to a sham procedure in which the joint space was violated but the meniscus was not. After being allowed subsequent free movement in individual dog runs, the animals presently are being sacrificed at either 13 or 26 weeks postoperatively.

Several related test protocols have been developed and are being applied for assessment of biomechanical function. Tests are performed on both the operated limb and the unoperated one so that results can be normalized and compared from animal to animal. First, quasi-static joint load/displacement curves and meniscal hoop strain are measured at different joint angles. The loads are applied with an Instron test machine and displacements and strains are measured with resistance strain gauge extensometers. A multi-channel, analog-to-digital data acquisition, conversion and processing system has been developed for collecting these data, displaying load/displacement curves and computing structural stiffness.

Next, the pressure distribution pattern of the meniscus on the tibia as a result of femoral loading is obtained with pressure-sensitive film introduced between the meniscus and the tibia. The load-bearing area is determined on the film with a digitizing pad and associated software developed for bone histomorphometry measurements. Then, the maximum pressure and its point of application are measured with a commercial densitometer designed for use with the pressure-sensitive film.

Finally, the meniscal tissue is excised and its approximate strength and stiffness in tension are determined on another Instron machine. Special fixtures have been developed for gripping the tissue. A histologic assessment of healing also is being performed on the repaired tissues, and articular surfaces adjacent to the repaired menisci are being examined for damage.

Future Plans—It is expected that testing will be completed in the next three months. If meniscal repair can be shown to be biomechanically effective, the hypothesis that such repairs can be expected to minimize post-injury incidence and severity of degenerative arthritis in the knee will be strengthened substantially.

Biomechanics of Hip and Knee (Human)

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Sponsor: National Institutes of Health

Purpose—This research is directed towards the advancement of our understanding of the biomechanics of the hip and knee. The work involves a documentation of hip and knee mechanics in normal subjects, patients with degenerative joint disease, and patients with surgical reconstruction of their joints, during a variety of daily activities. This research specifically involves the development of a three-dimensional model of the lower extremity including origin and insertion points of all muscles about the hip and knee (and selected muscles about the ankle) and origin and insertion points of knee (and ankle) ligaments. This model is utilized in an investigation of various schemes to distribute calculated intersegmental resultant forces and moments about the hip and knee to the actual anatomic structures carrying these loads.

A validation of this distribution investigation is being conducted in normal and pathological situations utilizing EMG recordings. This investigation will finally result in the collection as well as reporting of data on the mechanical function of the hip and knee. This is necessary to rationally design, utilize, and evaluate various treatment modalities.

Biomechanics of Anterior Cruciate Ligament Reconstructions (Dogs)

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Sponsor: National Institutes of Health

Purpose—The biomechanical parameters underlying reconstruction of the anterior cruciate ligament (ACL) of the knee have been incompletely studied. The ACL is frequently totally disrupted in athletic trauma and other accidents. Since the ACL is important in the kinematics of the knee, its correct function is vital in maintaining joint integrity. We will utilize a proven Hall-effect displacement

transducer to measure ligament strain prior to and immediately following ligament reconstruction in canines. The same technique will be used as part of the measure of function after two year's rehabilitation.

At two years, we also will measure the strength of the ligament at the time of sacrifice. We will relate a composite score of function and joint pathology to the biomechanical quality of the original reconstruction. The functional score of the reconstructed and control groups will be compared. Thus, we will establish the importance of the original strain pattern of the ACL as well as clarifying the ability of the reconstruction to mimic the biomechanical functions of the ACL.

In a related study, the protective function of casts, cast braces and other braces commonly used following ACL reconstructions will be compared in human cadavers using the Hall-effect device. Similation of appropriate motion and muscle function (isometric in totally restrictive devices such as casts and locked braces, and limited isotonic activity in partially mobile braces and cast braces) while measuring the ACL strain should allow clarification of the safest means of knee rehabilitation.

Ligamentous Knee Stability-Combined Clinical Loadings (Human)

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Sponsor: National Institutes of Health

Purpose—Ligamentous stability of the knee will be quantified *in vivo* and *in vitro* by direct measurement of force versus displacement responses for anterior-posterior tibial drawer, moment versus rotation responses for varus/valgus angulation of the tibia, and 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 an 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 knee injuries 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.

A. Joint Studies

3. Upper Limb

Static Force and Stability Analysis of Human Elbow

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Sponsor: National Institutes of Health

Purpose — The renewal project will continue the specific aims of: 1) development of a physiologically equivalent normative model of the elbow joint for force analysis; 2) determination of the muscle and joint forces during various functions; 3) verification of the theoretical results; 4) examination of the relative contribution of individual joint support elements (articular surfaces, ligaments, and capsules) to joint stability; and 5) decomposition of the resultant joint forces and moments into each support element. Data for establishing the normative model will be obtained by biplanar X-ray and direct force measurement methods.

In resolving the indeterminate force analysis problem, the method of introducing additional constraint equations based on physiological and pathological considerations combined with the optimization method will be used. The theoretical results will be verified by both qualitative and quantitative electromyographic studies. The relative contribution of the joint support elements in resisting external load at the joint will be measured by performing load-displacement tests of the intact joint followed by sequential sectioning of individual elements. The joint contact area will be obtained by reversible cartilage staining technique and computerized tomography. The decomposition of the joint load will be achieved analytically. The results of this study can be applied to numerous clinical problems, including the design of total elbow arthroplasty components and diagnosis and treatment of the ever-increasing athletic and traumatic afflictions of the elbow joint.

Biomechanical Study of the Radial Ulnar Carpal Joint (Human)

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Purpose — Chronic pain and clicking about the distal radial ulnar and ulnocarpal joint associated with weakness of grip and a subjective sensation of wrist instability are frequently results of a healed Colles fracture. This fracture can be a dislocated or subluxed distal radial ulnar joint, arthritic involvement of the wrist, or more frequently, a seemingly rather insignificant wrist injury. Many surgical and nonsurgical treatments deal with these symptoms without the full knowledge of the cause of the symptoms. This is a direct result of the lack of understanding of anatomic and biomechanical interrelationships of the wrist components in normal and pathological situations.

This research program proposes to further pursue our investigation into the anatomy and function of the ulnar aspect of the wrist. Using the techniques developed in the ongoing Biomechanical Study of the Radial Ulnar Carpal Joint, radioulnar carpal, and intercarpal forces and pressures will be studied in the intact

wrist as well as in surgically altered wrists (e.g. ulnar shortening, distal ulnar resection, distal ulnar Silastic replacement, carpal resections, etc.). The analysis of the effect of these operative procedures on the normal wrist biomechanics would lead to recommendations regarding the efficacy of previously recommended treatment modalities for different wrist problems. Improved treatment protocols for specific pathological conditions of the wrist would be forthcoming based on sound biomechanical principles with predictable long-term results.

Influence of Wrist Pathomechanics on Hand Function (Human)

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Sponsor: National Institutes of Health

Purpose — The overall objective of this research is to advance our understanding of normal and pathologic wrist mechanics. This includes an understanding of the role that individual wrist components (e.g., carpal bones and wrist ligaments) play in producing normal wrist function, an understanding of the disruption of normal wrist function caused by rheumatoid arthritis, and a better understanding of the mechanics of surgical reconstruction of the joint.

Functional Forces in Normal and Abnormal Fingers (Human)

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Sponsor: National Institutes of Health

Purpose — This project attempts to achieve the following objectives: 1) analyze joint, tendon and capsuloligamentous forces in normal and abnormal fingers and thumbs; 2) study the pathomechanics of the fingers and thumbs and their surgical treatment methods; 3) perform objective functional evaluation of hand patients before and after treatment; and 4) correlate the predicted muscle forces and their EMG measurements.

Progress — Normative models for each finger and the thumb have been established based on a precision biplanar X-ray method using marked cadaver specimens. The optimization technique combined with the permutation method and functional grouping have been adopted for force prediction. Quantitative EMG data on normal subjects have been used to correlate the theoretically estimated results. The cross-sectional technique was found to be ineffective in quantitating capsuloligamentous geometry, and it has been replaced by a stereo-video method using high resolution TV cameras. Collateral ligaments of the MCP joints have been studied with improved results. Modeling of the joint capsuloligamentous structure will be achieved using equipollent force analysis. Cadaver finger and joint specimens will be tested on a MTS machine to determine joint contact points and ligament tension to facilitate mathematical modeling. Three groups of patients are being evaluated using the objective method developed from this project to assess their functional deficits and treatment results. Normal subjects also have been studied to establish the reference database. Hand pathological conditions involving joint deformation and strength loss are being studied. The results will be used to evaluate diagnosis and treatment of alternatives.

Mechanics of Control of Movement of Human Elbow Joint

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Sponsor: National Institutes of Health

Purpose — The role of proprioceptive reflexes during active movement is still a matter of controversy despite decades of study. Arguments have focused on what mechanical variable (e.g., muscle length, force) the central drive tries to control during movement. The proposed research addresses the question of what does the central drive accomplish, i.e., what combination of mechanical variables is found to be regulated in postural states and controlled during active movement. There is support that the variable regulated by proprioceptive reflexes is a simple combination of muscle length and force.

This hypothesis is often referred to as "stiffness regulation." For measurements on a joint, the regulated variable translates into a combination of joint angle and joint torque provided there is no co-contraction of antagonists. However, it is not clear whether the dynamic changes in torque and angle that ensue when a perturbation is imposed on the joint are a reflection of the inertia and damping associated with the joint or reflect, or the speed of response of the regulatory system. The first aim is to identify the regulated variable while the joint angle and torque change dynamically in response to perturbation. The second aim is to determine whether or not the combination of mechanical variables that was found to be regulated in postural states is what is controlled during active movement. The third and fourth aims address questions related to the commonly observed contraction of antagonist muscles when the need for such contraction is not apparent. Specifically, what external conditions are sufficient to elicit contraction of antagonists and how is the electromyographic stretch reflex of the antagonists affected? Answers would provide an understanding of the role of proprioceptive reflexes in the control of movement by healthy subjects. Such an understanding is a necessary prerequisite for delineation of the role these reflexes play in pathological conditions characterized by movement disorders.

B. Spine

Mathematical Modeling of the Human Spine: Implications to the Orthotic Management of Spinal Deformities

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Sponsor: VA Rehabilitation Research and Development Service

Purpose — Mild to moderate curvatures of the spine are most often treated conservatively using an orthosis such as the Milwaukee brace or the Wilmington jacket. The mechanics of curve progression is of considerable interest to the clinician due to its implications to patient selection for the orthotic treatment as well as the choice of an orthosis.

The purpose of this study is to investigate the stability of a scoliotic curve with and without bracing as a function of the degree of initial curvature (at the time of orthotic intervention) and the amount of stabilizing transverse load exerted by an

orthosis on the spinal curve. Mathematical modeling of the spine-orthosis system involves inelastic buckling analysis of an initially curved and transversely loaded flexible column. The model can stimulate the interaction of different types of orthoses with the spinal curve.

Progress — This analysis examines the stability of an unsupported (without an orthosis) scoliotic spine as a function of: the magnitude of the curvature; and the curve pattern, such as single, double major, or primary and compensatory curves. Furthermore, it evaluates the stability of an orthotically supported scoliotic spine as a function of: the magnitude of the curvature, the end support conditions indicating the extent of motion constraint imposed by an orthosis on the ends of the curve, and the magnitude and type of the stabilizing transverse load exerted by an orthosis on the curve.

Preliminary Results — This study provides a biomechanical explanation as to why larger curves are more progressive than smaller curves, and why a brace is only effective in small and moderate degrees of curvature. Furthermore, this study shows that a double major curve has a greater load-carrying capacity and, therefore, is more stable than a comparable single curve with a compensatory curvature. These results are in general agreement with the clinical findings based upon retrospective studies of patients undergoing orthotic management for scoliosis.

Mechanical Analysis of Cervical Spine Stabilization Techniques

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Sponsor: VA Rehabilitation Research and Development Service

Purpose — The objective of this study is to develop a methodology for analysis of spinal motion with controlled loading, apply this methodology to accepted types of posterior cervical spine stabilization, and develop and test an improved stabilization method.

Progress — Previous reports have described a successful method of determining force-displacement behavior of a cervical segment. Using this method, posterior stabilization techniques were tested for a flexion-distraction lesion at C5-6 and compared with each other as well as the intact spine. We found that interspinous wiring was effective in restricting flexion-extension, but may not provide enough stability with torsional and lateral bending forces. A segmental wiring technique simulated the stiffness of the intact spine in all planes but allowed less excursion at higher forces.

Preliminary Results — Over the past year, a posterior stabilization device has been designed, prototyped, and revised. The design objective of the device was to retain the stability advantages of both interspinous wiring and segmental wiring techniques while discarding the complexity of application and lack of versatility of the segmental wiring techniques. The device consists of a set of laminar clips which do not invade the neural canal or facet joints coupled together with rigid struts which may be conformed to many configurations. The device has been successfully tested on preserved cervical spines.

At present, the new device is being tested on fresh cadaver cervical spines using the methods previously described. Comparisons will be made with the intact spine as well as the fixation technology previously tested.

Results of this study are currently being used to assist in selecting the appropriate stabilization technique for disruptions of the cervical spine.

Effects of Low Back Pain Treatment Modalities on Lumbar Facet Loading

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Purpose — A majority of those who comprise the working population in the United States will suffer from low back pain and sciatica at some time in their lives. Many times these symptoms are secondary to derangements of the lumbar intervertebral disc. A common accompaniment to disc disease is facet arthropathy. Treatment options for lumbar disc disease include discectomy and chymopapain injection, which alter the load-bearing behavior of the disc. Clinical and experimental evidence indicates that an alteration in the mechanical behavior of the disc produces loss of alignment and abnormal movement and loading of the facet joints. The resulting changes may lead to progressive degeneration of the facets, development of osteoarthritis, and back pain.

The objective of this study is to obtain data describing alterations in load-bearing characteristics of facet joints of lumbar spine segments following simulated treatment modalities for lumbar disc disease. During this study we will test cadaver spine specimens as a function of treatment modalities and physiological load types for various lordotic configurations of the lumbosacral spine. We will also measure facet joint loads using a pressure sensitive film inserted between the articulating facet surfaces at L3-4, L4-5, and L5-S1 segments before and after discectomy or chymopapain injection at L4-5 disc.

Future Plans — With data, we will have a rational basis to design clinical trials for a physician to use in choosing between two effective treatments, especially in the case of patients with pre-existing pathology in facet joints. The data will also help establish guidelines for prescribing post-treatment activities in such patients.

Clinical Biomechanics of the Cervical Spine (Human)

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Sponsor: National Institutes of Health

Purpose — Injuries of the cervical spine represent one of the most physically disabling injuries compatible with survival. They cost the society an estimated three quarters of a billion dollars per year in the United States. Although there have been a multitude of clinical studies, there are only a few studies that have been attempted to analyze the various surgical decompression and stabilization procedures that are used for the cervical spine trauma patient. The purpose of the present proposal is to study a realistic cervical spine injury model regarding changes in its stability due to several surgical decompression and stabilization procedures. Fresh cadaver cervical spine specimens will be utilized to model the

clinically relevant hyperflexion injury. Surgical decompression procedures, e.g., laminectomy and facetectomy, also will be modeled as well as several surgical stabilization procedures. The immediate stability of the spine models as well as their failure strengths will be determined. One of the most significant aspects of the experimental protocol is the determination of a three-dimensional stability of the injury model after every injury and stabilization procedure utilizing the 3-D spinal motion measurement techniques pioneered at the Yale Biomechanics Laboratory. The significance of the proposed study will be in several different areas. The results will provide a direct measurement of the relative loss of stability due to a decompression procedure as well as a relative evaluation of the various surgical stabilization procedures. Additionally, 3-D physical understanding of the entire lower cervical spine will be determined to provide a better understanding of the mechanics of normal, injured, and surgically stabilized cervical spines.

Three-Dimensional Kinematics of the Lumbar Spine (Human)

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Sponsor: National Institutes of Health

Purpose — Based on the significant findings of the preliminary study conducted by the investigators, a 3-year research program is proposed to study three-dimensional kinematics involving range and pattern of motion of segments obtained from 30 fresh cadaver lumbar spine specimens. The objective of the proposed research will be met by conducting *in vitro* experiments using the test facilities and instrumentations specially designed, developed, and tested for this purpose. In addition to the traditional modes (Flexion/Extension, Lateral bending, and Axial rotation), three-dimensional motion of the lumbar spine will be studied in 10 other loading planes (15 degrees apart) that lie in between sagittal and frontal planes. All modes of motion of the lumbar segments will be studied (with and without compressive preload) for the independently and incrementally applied moment loads and shear loads. The kinematic data will be obtained under four conditions: 1) intact motion segment; 2) motion segments with posterior elements transected; 3) motion segments with transected posterior half of the intervertebral disc; and 4) motion segments with transected anterior half of the intervertebral disc. The three-dimensional kinematic characteristics of the lumbar motion segments will be studied in terms of the following kinematic parameters: 1) range of motion in each plane of loading in terms of total rotation and translation about and parallel to the screw axis, and their motion components along the three mutually perpendicular axes of a reference system; and 2) parameters of the screw axis in terms of direction cosines and coordinates of the point of intersection of the screw with a prescribed plane. A total of 30 lumbar spine cadaver specimens will be tested. The data collected from the motion segments of these specimens will be analyzed statistically to test the differences in means of kinematic parameters of the intervertebral motion. The significant contribution of the proposed research will be to provide the signature data or description of the 3-D kinematics of vertebral motion and its normal variation in a quantitative form for each level of the intact and transected motion-segments of the human lumbar spine.

Biomechanical Studies of Idiopathic Scoliosis (Human)

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Sponsor: National Institutes of Health

Purpose — Idiopathic scoliosis is a disease in which the spine develops a progressive curvature. Its cause is unknown and if untreated, it may result in gross deformity. Approximately one person in 500 suffers from this disease.

The overall purpose of this investigation is: 1) to develop a better understanding of the mechanical factors involved in the initiation and progression of idiopathic scoliosis; and 2) to apply this information to improve the methods of treatment and to develop means of prevention.

Because of the difficulty of dealing with the anatomical complexity of the vertebral column, a basic feature of this program is the use of a computer-generated analog of the spine. Studies of model scoliotic spines will be made in conjunction with clinical studies to provide vital information regarding the three-dimensional morphology of the curves, their progression, and their correction. The knowledge gained from these studies will help to base treatment on more rational and objective grounds, and the understanding provided may be essential to the discovery of its etiology.

The Traumatology of the Head and Spine (Monkey, Human)

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Sponsor: National Institutes of Health

Purpose — The project is concerned with the dynamic behavior of the brain and spinal cord under impact loading. The main focus will be the construction of structural finite-element computer models of the human and rhesus head and neck. To support the above goal, we propose to: 1) exercise the first-generation, linear finite-element (FE) computer model of the human head and neck to crown impact with and without padding protection; 2) improve the capability of the present FE model by including nonlinear material and geometric properties in its formulation. By so doing, we should extend the ability of the FE model to simulate contact and noncontact impact situations where large displacement and finite strains are expected in the head and neck; 3) construct a similar dynamic model for the rhesus head and neck; 4) perform dynamic tests on fresh human and rhesus autopsy cervical spines to determine its mechanical and failure characteristics in tension, compression, flexion, extension, lateral bending and torsion (These data are prerequisites to a realistic large displacement FE model.); 5) use the technique of computerized tomography (CT) to determine the geometry and inertial tensor of the rhesus head and neck prior to trauma. The post-trauma CT scans will be used to detect the primary traumatic lesion sites; 6) validation studies, using four rhesus monkeys per year, will be undertaken to verify the effects of the impact vectors on the field quantitites; e.g., linear and angular head accelerations, dynamic intracranial pressure and CT lesions. Four will be used in superior-inferior, occipital and temporal head impacts; and 7) inasmuch as these are very expensive monkeys, we are obliged to do the neuropathology even though they only indirectly support the FE effort. The brains and spinal cords of monkeys will be examined with standard neurohistologic procedures. Particular emphasis will be placed on axon degeneration using silver techniques.

Structural and Mechanical Properties of the Spine (Human)

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Sponsor: National Institutes of Health

Purpose — Our on-going research seeks to identify intradiscal pressure variation both within the intervertebral disc as well as over the end plates. Physiological loading is being carried on unembalmed lower thoracic and lumbar segments at known eccentricities. These data will be used to formulate a finite element model of the disc so that a finite element model of a vertebral segment can be developed.

Characterization of Morphologic Changes in Scoliosis (Human)

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Sponsor: National Institutes of Health

Purpose — The proposed research project will utilize a proven system of *in vivo* three-dimensional radiographic analysis to study both the early- and long-term morphologic changes associated with the idiopathic adolescent spine. Three major categories of scoliosis treatment will be studied—observational, bracing, and fusion. Specifically, this study will be directed towards documenting the effects of growth and treatment on the three-dimensional morphology in the idiopathic adolescent scoliotic spine. The study results will also be evaluated to determine if there exist predicators of not only the progression of the untreated deformity, but also the relative success or failure of standard treatment programs.

Mechanism of Cervical Spine Injuries

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Sponsor: National Institutes of Health

Purpose — The purpose of this project is to produce clinically relevant injuries in cervical spine specimens under controlled high-speed trauma. Load measurements during trauma and plain X-rays, CT scans, and three-dimensional stability measurements are to be carried out before and after trauma to provide an assessment of the loss of stability due to trauma.

Progress — A trauma-producing apparatus has been constructed and is functional. It consists of a drop tower with a vertically oriented tube in which weights of varying magnitude may be dropped from different heights. At the base is a specimen-holding table that can locate the specimen in any orientation and position with respect to the falling weight. A multi-dimensional load cell is provided between the specimen and the positioning table. A separate machine for measuring three-dimensional stability of the specimen, before and after trauma, has been designed and constructed. Presently, studies are being carried out to evaluate the machine.

The deformation of the specimen during trauma will be documented with the help of a high-speed (3,000–6,000 frames per second) 16 mm movie camera. A couple of tests have been conducted using spine specimens and a demonstration model of a high-speed movie camera, in which the results were successful. Finally, 30 canine spine specimens have been prepared for the first series of tests.

C. Human Locomotion and Gait Training

[*See also pgs. 10, 19, 35, 57, 59, 60, 61, 62, 275*]

A Low-Cost Gait Recording System

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Sponsor: Northern Ireland Prosthetics, Orthotics and Aids Service

Purpose—The aim is to produce a low-cost, modular, portable system that will allow clinicians to record some parameters of gait. It will permit clinicians to carry out comparisons of gait measurements over long periods of time, and to provide an analysis of the gait pattern.

The Foot Pressure Profile Platform (FPPP) is a low-profile plate with 512 load cells that depict and analyze discrete areas of pressure beneath the foot. There is an electrogoniometric system for measuring the angular movements of joints, and a step mat which depicts stride length and timing. All are interfaced with a low-cost BBC computer. The system can be used in hospitals without architectural alterations, and is easily set up for use.

The FPPP is now in production, and can be programmed to suit individual clinical needs, and the electrogoniometers and step mat are in the process of being integrated into the system. The modules can be integrated separately with the computer, and software can be provided according to need.

Biomechanical Study of Standing and Walking Using Force Plates

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Sponsor: National Rehabilitation Center for the Disabled

Purpose—The objectives of this project are: 1) to establish fundamental biomechanical relationships between center of gravity (c.g.), point of application (p.a.), and ground reaction forces; 2) to estimate the movement of c.g. during human standing and walking by using above relationships; and 3) to develop clinical methods for evaluation of standing and walking performance.

Progress—Commercial force plates (Kistler, 9281B) were used to measure ground reaction forces. A data processing system used in earlier stages included PDP-12 and NOVA-4, and currently HP Model 216 is used.

Preliminary Results—Results and findings through these studies are as follows. Exact expressions for determination of p.a. were derived. These formulae indicate that conventional simple expressions are only approximations under particular conditions which may be satisfied in the ordinary conditions of standing and walking. Fundamental relationships between mechanical parameters, including c.g., p.a., forces and time derivative of angular momentum, were derived. Using above relationships and curve fitting method, movement of c.g. during standing and walking was estimated. From above relationships and measured data, it was evident that fluctuations of p.a. had reflected feature of the force fluctuations. A new index derived from the force record was used to evaluate characteristics during standing. Force fluctuation levels during quiet standing were only slightly higher than those during sitting. The movement of c.g. during

quiet standing seemed to be influenced by respiratory activity and not directly correlated with muscle effort. Basic patterns of force records during walking can be explained by biomechanical interpretaton of c.g., p.a. and force data. During the curve fitting study, it was found that zero level of horizontal force component of the force plate output shifted slightly according to the location of the load (p.a.) and that this zero shift introduced errors in c.g. curve. Better results were obtained after correction of the shift.

Future Plans — Efforts continue to obtain a more comprehensive understanding of standing and walking, and to develop clinical methods for evaluation of standing and walking performance from force data, as well as simple devices to measure standing and walking activities for clinical use.

Assessment of the Effectiveness of Gait in Cerebral Palsy Children

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Sponsor: Scientific and Research Trust, Central Remedial Clinic

Purpose — It is possible to formulate a reliable and objective assessment procedure of the gait of children with cerebral palsy who are independent walkers. This assessment procedure would: 1) help to categorize children in terms of the severity of their disability; 2) it would be easily administered by any physiotherapist with basic pediatric training; and 3) it would be possible to administer in any physiotherapy department requiring the minimum of time, equipment, and expense.

Progress — A total of 60 were included in the project, 30 children with cerebral palsy and 30 non-physically handicapped children. All were between the ages of 4 and 15 years and were independent walkers. All normal children were excluded from having pre- or post-natal problems or any orthopaedic intervention. The study was divided into 3 parts. These included: 1) measuring temporal and linear components and observing the pattern of gait; 2) assessing functional ability; and 3) assessing endurance.

We hope to correlate the temporal and linear components with specific changes in functional ability.

Preliminary Results — While the study is not yet complete, preliminary results show a highly significant difference for velocity (>0.001) with normal children walking faster. There is a significant difference for cadence ($p<0.001$) with normal children showing higher cadence. There also appears to be a highly significant difference ($p>0.05$) for the degree deviation from the expected line of progression. There was no significant correlation between velocity and cadence in cerebral palsy subjects.

In the category of functional abilities, there is an expected highly significant difference between normal and cerebral palsy subjects with $p > 0.0001$. Normal subjects also show greater endurance and require less recovery time. Results appear to be highly similar between all therapists and each child, except for one therapist and one child. On cross-examination of the results, there appears to be no difference between tests taking places, and the child's cooperation and motivation appear to be influencing factors.

A Telemetric Data Acquisition and Processing System for Biofeedback Training and as a Diagnostic Aid for Human Movement Training

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Sponsor: National Institute of Handicapped Research

Purpose — This work is a continuation of a past effort which began with the specific aim of improving gait training of above-knee amputees. The result of previous work was a self-contained portable force and movement measurement system that provided biofeedback of gait parameters. Two transducers, weight and hip angle, were developed and integrated into the MIT STRIDER system. The STRIDER has been used and evaluated by the physical therapy staff at the Massachusetts General Hospital (MGH), and their reactions were enthusiastic.

During the past 7 months, the STRIDER was again used by therapists at MGH. At their request, several small changes were made to enhance performance. For example, an amplifying speaker was added to allow both the patient and therapist to hear the biofeedback without earphones.

Progress — Currently, the second version of the system is being designed and developed. Measurements from the same transducers are put in to a personal computer via a telemetry data transmission system. The personal computer increases the flexibility of the system in many ways. The therapist can alter threshold values and choose among various forms of biofeedback both visual and audio. Also, data analysis can be accomplished with relative ease. Another benefit is the reduction of the size and weight of devices worn by the patient.

A telemetry system has been chosen as well. Alternatives include infrared, AM and FM radio transmission systems. Design parameters such as performance, reliability, and transmitter size were used in evaluating prototype transmission systems. The final choice was to use an FM transmitter/receiver.

Circuitry to interface the STRIDER transducers with the new system have been developed. Through use of voltage to frequency converters, analog signals from the transducers are coded for FM transmission.

Currently, several formats for visual biofeedback via the personal computer are being studied. The goal is to design CRT-based displays which are effective and versatile.

Evaluation of Methods to Measure Locomotion Performance and Activity

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Sponsor: National Institute of Handicapped Research

Purpose — There are now a number of relatively inexpensive methods of measuring characteristics of gait in individual patients and assessing the amount of activity carried out by them. Some of these methods are designed primarily for clinical use; others offer possibilities for evaluating usefulness of experimental devices and treatment methods not available before.

Among the systems being studied are the Moss Gait Mat, a four-channel physiological ambulatory monitoring device that will record the number of steps and heart beats against time for 24 hours, and 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.

The Moss Gait Mat has been installed in the Physical Therapy Area and is used routinely with rehabilitation patients. It also is being used to record data before and after treatment in the experimental arthritis treatment programs.

Progress — The past year has been spent in developing a system for counting the heart beats and steps recorded by the four-channel unit. The system is ready for evaluation of sensitivity by recording data that are obtained as the alignment of an above-knee prosthesis. The four-channel physiological equipment should be very valuable in evaluation of prostheses and orthoses.

Quantitative Gait Analysis (Human)

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Sponsor: National Institutes of Health

Purpose — Quantitative gait analysis using computer-aided videomotion analysis, force plates, and electromyography is of recognized value in assessment of gait disabilities and in quantitative evaluation of treatment. Despite dramatic improvements in techniques, gait analysis still lacks widespread clinical utility because of uncertainties relating to data selection, manipulation, and analysis. Since data acquisition is usually limited to a single test session over several gait cycles, one vital problem concerns selection of a gait cycle for analysis that is representative of the patient's gait and is reliable as a basis for clinical decision-making. Another problem relates to the manipulation of large quantities of data generated by measurements of various kinetic, kinematic and electromyographic parameters over several gait cycles to detect clinically significant patterns of performance. This process is further complicated by the fact that gait patterns vary among patients with the same syndrome and, to a certain extent, among normals.

Interpretation may be simplified by using statistical pattern recognition techniques. In order for this approach to be successful, the enormous quantity of data must be reduced to a parsimonious set of features which describe gait patterns accurately. Furthermore, representation of graphic patterns associated with various gait parameters in terms of a discrete set of variables would make numerical comparison more meaningful.

The first part of this study will investigate repeatability and clinical reliability of selected kinetic, kinematic, and electromyographic parameters obtained from repeated gait analyses on normal subjects and two representative groups of orthopaedic patients. The feasibility of using the variance ratio as a criterion for averaging gait cycles to yield a representative cycle also will be examined. The second part of the study will deal with the application of a principal component analysis for representing gait patterns in a concise manner as an initial step to application of pattern recognition techniques.

The effectiveness of the derived features in representing gait abnormalities will be evaluated using the same normal and orthopaedic patient subjects. The results of the proposed study will enhance the clinical effectiveness of quantitative gait analysis by defining practical computer algorithms for selecting and assessing reliability of raw gait data, and by defining techniques for feature selection that can be used effectively in pattern recognition techniques.

Weight Distribution in the Foot Before and After Surgical and Orthotic Intervention for Hallux Rigidus

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Sponsor: Langer Biomechanics, Inc.

Purpose — Hallux valgus deformity with limited motion and pain in the first metatarsophalangeal joint is associated with abnormal weight distribution through the foot in ambulation. A common treatment modality for this condition is the Keller surgical procedure with a total implant and the use of a functional posted foot orthosis postoperatively.

The goal of this study is to evaluate the efficacy of both the surgical technique and the functional posted foot orthosis in improving the biomechanics of the pathological foot in ambulation. In this study we will measure the parameters characterizing the development of weight distribution patterns in the foot (from heel contact through toe-off) within the environment of the shoe using the electrodynogram (EDG). Our subjects for this study will be patients who have been scheduled for the Keller procedure with a total implant at the Hines VA Hospital. We will complete the study over 12 months both pre and postoperatively as well as with and without the orthosis after surgery.

D. Upper Limb Function

Shoulder Stabilization, the Spinal Accessory Nerve, and the Trapezius Muscle

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Sponsor: No funding was associated with this study

Purpose — The purpose of this study is to show that the trapezius muscle, with its spinal accessory innervation, is a very important factor in shoulder girdle stability. Cervical nerves may supply trapezius motor innervation in varying amounts. Methodology consisted of: 1) anatomic dissections; and 2) a retrospective clinical review of objective and subjective findings in 11 male patients, ages 48 to 72 (average age 62), in whom the spinal accessory nerve was surgically removed during head and neck cancer operations.

Anatomic dissections displayed the dual innervation of the trapezius muscle by the spinal accessory and cervical nerves. The clinical review similarly showed that major but varying motor innervation is from the spinal accessory nerve. All patients had drop and internal rotation of the affected shoulder with scapular winging. Abduction in the eight patients measured ranged from 45 to 100 degrees, the average, 73 degrees and the normal, 180 degrees. Forward flexion measured in seven patients ranged from 60 to 140 degrees, the average, 112 degrees and the normal, 180 degrees. With the loss of the trapezius function, the greater humeral tuberosity is unable to pass under the coracoid ligament and the scapula does not rotate, both limiting abduction. In three shoulders measured, muscle weakness generally occurred. Strength ranged from two to four on a scale of one to five, where five was the strongest.

Collectively, these findings indicated a subluxed, unstable shoulder. Subjec-

tively, all nine patients, who could be questioned, had head, neck, and shoulder pain. However severe at first, most patients learned to accommodate the pain. Only one of 11 patients was able to return to work or hobbies, but only briefly, because of the recurrent disease.

We conclude that the trapezius muscle is very important in stabilizing the shoulder joint as it depends chiefly on the spinal accessory nerve for motor supply. Part of motor innervation, however, may be from the cervical nerves. Variations in this dual motor innervation may account in part for variable loss of motor power with loss of the spinal accessory nerve.

E. Other

Control of Metrical and Timing Precision in Human Movement

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Sponsor: National Institutes of Health

Purpose — This study proposes to investigate central nervous system control strategies used to produce accurate movements. Control of voluntary movement is viewed in this study as a stratified process with several levels of control: 1) movements are initiated by high level construction of open-loop motor commands; 2) are executed from a reference frame stabilized by a postural control system and; 3) are modified by sensory feedback during both command execution ("concurrent feedback") and after movement completion using knowledge of results ("delayed feedback"). Skilled movements and isometric force production are evaluated in terms of these three control mechanisms.

Human adult subjects will track various waveforms presented on a visual display by exerting force on a manipulandum with their elbow musculature. Comparison will be made of motor accuracy under a variety of conditions affecting: 1) the predictability of the stimulus (tracking waveform) amplitude; 2) the availability of visual feedback; 3) the degree of postural stability; and 4) the movement of the elbow joint. In most experiments, subjects will track step waveforms on an oscilloscope screen, while, in one experiment designed to distinguish between strategies subserving timing and metrical movement precision, graphical displays will be more complex. Electromyographic activity will be recorded from appropriate muscles during tracking experiments in order to characterize movement strategies at a level of peripheral neural commands to muscles.

Amputees fitted with myoelectrically-controlled arm prostheses will be used in several phases of this study. In one experiment, these individuals will be used as models of the "deafferented arm" in order to characterize this role of peripheral somesthetic feedback in the control of accurate movements in normal subjects. In addition, a pilot experiment is proposed which directly addresses the problem of user control of multiple degree-of-freedom powered arms. It is hoped that the latter experiment will lead to the development of a large-scale research and training program for amputees at Good Samaritan Hospital and Medical Center.

Human Response and Lower Extremity Injury

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Sponsor: National Institutes of Health

Purpose — The mechanics of human injury is a complex process whereby external forces are transmitted to the human musculo-skeletal system. This system responds in the manner of displacements and rotations and stresses are induced in the tissues, and in some conditions, the tissues are disrupted. When the forces are not constant, prediction 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 the lower extremity injury rate is high and the forces transmitted to the foot can be measured. Response of the lower extremity also can be measured and 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 and the rotations occurring at the ankle, knee, and pelvis. Integrated EMG from muscle groups during skiing and especially during falling, when severe loading occurs and the likelihood of injury increases, also have been measured and analyzed. The field measurements identify the injury environment and the laboratory experiments clarify how the lower extremity responds to dynamic loading. 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 small compared to typical tibia fracture strength and knee ligament strength will be corrected. The erroneous concept is widespread, extending to standard organizations, the industry and the public alike. The error has a 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 develop meaningful standards of safety.

Biomechanics of Human Skin

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Sponsor: National Institutes of Health

Purpose — A series of *in vitro* biaxial stress-strain experiments will be performed on rectangular sheets of unembalmed human skin. The purpose is to quantify the anisotropic, viscoelastic response of the dermis to time-varying strains applied simultaneously in orthogonal axes. The stress relaxation and creep characteristics of skin in a biaxial loading environment also will be studied. A governing biaxial constitutive equation for the dermis will be developed based on a material strain energy formulation. These tasks will be addressed for tissue from various anatomic regions to quantify differences in response associated with physiologic function.

A second primary goal is to identify a material property of the dermis, the energy of tearing. This constant describes the tensile failure characteristics of crack or tear propagation in thin sheets of material undergoing large deformations. The tearing energy constant will be quantified from measurements of applied force, displacement, and geometry of simple test specimen configura-

tions. Both the biaxial stress-strain and failure studies will quantify fundamental material properties and response characteristics of normal tissue which are not available from uniaxial test protocols. These data are necessary for rational planning of elective surgical incisions and finite element analyses of proposed closure techniques. In addition, the intelligent design of dermal prostheses requires a knowledge of the skin's mechanical stress-strain behavior in complex loading environments present *in vivo*.

A Model to Study the Mechanical Behavior of Osteoporotic Bone

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Sponsor: VA Rehabilitation Research and Development Service

Purpose — Osteoporosis, characterized by a decreased mineral mass, is the most common metabolic bone disease in the United States and has been estimated to affect at least 6 million elderly American men and women. Although the cause of osteoporosis is unknown, it is multifactorial with contributing factors that include reduced physical activity, decreased dietary calcium, and genetics, hormonal, and other related disease states. Osteoporosis is not a severe problem in itself but problems often arise from its complications. An increased incidence of vertebral compression fractures and as many as 100,000 broken wrists each year may be attributed to osteoporosis. Approximately 190,000 late middle age or older Americans fall and break their hips each year. As many as one-sixth of these patients may die from the ensuing complications, while many of the survivors are incapacitated. The late middle or older age group also represents the patient population most likely to require prosthetic joint replacement which may be compromised by osteoporosis.

Nutritional Secondary Hyperparathyroidism (NSH) is a generalized metabolic bone disease characterized by osteopenia, induced by a diet too low in calcium and/or too high in phosphorus. NSH can be induced in laboratory animals through dietary imbalances resulting in an osteoporotic-like condition of the bone. NSH induction is a potential model for studying the effects of osteoporosis on the mechanical behavior of bone and its interaction with a prosthetic device. This study is investigating the histologic characteristics of the osteoporosis resulting from NSH to determine the effect on the mechanical characteristics of the femur before and after femoral arthroplasty.

Stress Analysis of Internal Fracture Fixation of Long Bones

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Sponsor: VA Rehabilitation Research and Development Service

Purpose — The objectives of this study are to develop accurate, non-linear, three-dimensional finite element models of long bones treated with compression plate fixation. These models will incorporate a number of important features which exist *in vivo* and which previous investigators have neglected. With the inclusion of these features in these new models, significant differences in the amount of stress shielding may be predicted in comparison to previous models. This in turn may have important implications on present plate application techniques and on the design of future plates.

These models will allow all primary *in vivo* loading modes to be studied individually. These loading modes will include: bending in the plane of the screws with the plated side in tension (bending closed), bending in the plane of the screws with the plated side in compression (bending open), bending perpendicular to the plane of the screws, axial compression, and torsion. Through the use of non-linear, contact-with-friction elements, these models will include the effects of friction and relative motion between the screw heads and the plate and between the plate and the bone. The relationships between these motions and individual screw tightness will be examined parametrically in order to model different degrees of plate/bone fixity associated with different stages of fracture healing. Both intact and osteotomized bones will be modeled using a transversely isotropic material model for cortical bone. The effects of plate/bone conformity will be studied using two limiting idealizations of possible *in vivo* bone geometries. The concept of plate/bone conformity also will be studied in relation to specified amounts of plate prebending. Both plated and non-plated versions of each of these models will be generated in order to evaluate the extent of stress shielding in each loading mode as a result of plate application. The effect of plate material will be analyzed by altering the input material properties to correspond to the two most common plate materials in current use, *i.e.*, stainless steel and titanium alloy.

Validation experiments using *in vitro* models will be conducted for each of the finite element models. Both titanium alloy and stainless steel compression plates will be applied to tubular specimens having simplified geometries. The first geometry studied will be cylindrical having constant diameter. The two geometries for the plate/bone conformity studies will, in one case, have a larger diameter at each end than in the middle, and in the second case, have a larger diameter in the middle than at each end. Separate specimens will be made from bone and magnesium. Axial screw force will be controlled by monitoring the insertion torque applied to each screw. Pressure-sensitive films will be used to determine pressure distributions and contact areas between the plate and bone. Strain gauge will be mounted to the plate and to the bone to measure surface strains. The *in vitro* models will be loaded in all primary loading modes. The data from these tests will then be compared with the predictions from the finite element models.

Postural Sway in Down's Syndrome

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Sponsor: Liberty Mutual Insurance Company

Purpose — Down's syndrome, a leading cause of mental retardation, occurs in 1 out of 800 live births in the United States. Recent advances in genetics, as well as in education and social interventions, have focused attention on the needs and characteristics of children and adults with Down's syndrome. Much of the emphasis has been placed on the mental retardation and the medical problems of these individuals. Relatively little attention has been paid to their characteristic movement deficits, which usually include some degree of hypotonia, or over-relaxed muscles, and increased joint mobility. The nature and the cause of the hypotonia are unknown, but are presumed to be related in part to the small and poorly developed cerebellum that has been observed in postmortem studies of individuals with Down's syndrome.

Preliminary Results — During 1984, we began working in this area with the goal of augmenting our understanding of motor-control mechanisms in Down's syndrome and contributing to therapeutic programs for both children and adults. Preliminary tests examined the motor skills of 25 children with Down's syndrome between 10 and 15 years of age. Although the children showed overall deficits in their skills, they also showed considerable individual variation in achievement and quality of performance. Since all demonstrated difficulty with activities involving static balance, we then began to study mechanisms, using the force platform to measure postural sway. Fifteen children with Down's syndrome, five normal children, and five children with learning disabilities were tested in the Motion Analysis Laboratory. We have evaluated them in a natural stance and a stance with feet together. They have been evaluated in both stances with their eyes open and their eyes covered in order to ascertain the effect of vision. To date, the children with Down's syndrome have shown greater mean sway in both the anterior-posterior and the medial-lateral directions and greater length and area of sway.

Future Plans — During the next year, we plan to test an additional 55 children with Down's syndrome. These children are between 11 and 14 years of age and were part of a longitudinal study of motor development during their first 3 years of life. They will be compared with an equal number of normal children of the same chronological age. The study will include tests of motor skills including balance. Height and weight measurements and medical examinations will allow us to evaluate the inter-relationship of several other variables.

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

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Purpose — Our laboratory is currently examining the effects of aging and stress on bone mechanical, morphological, and biochemical properties. During maturation, there is a rapid increase in bone mineral followed by a more gradual increase until the third decade of life. With aging, and particularly following menopause, the opposite or a rapid and often debilitating loss of bone mineral may occur with subsequent bone failure. Bone is capable, however, of adapting to increased or decreased levels of activity or stress, and thus the aim of our research is to understand the mechanism(s) by which immature and mature bone adapts to different stress environments (i.e., bed rest — hypoactivity and exercise — hyperactivity), and from which clinical treatment of debilitating bone diseases and/or fractures in the aged and young population can be improved. Changes in bone geometric, biochemical, biomechanical, and piezoelectric properties are being examined.

Preliminary Results — Geometric, structural, and material properties of normal, growing rats and normal, growing primates have been studied. The results of these studies suggest that scalar relationships exist for biochemical and biomechanical properties of rat and primate cortical bone, and extrapolations of experimental data to humans may be possible. Recently completed studies on the

effects of hyperactivity (voluntary and involuntary exercise) and hypoactivity (hind limb suspended hypokinetic model) have provided insight into the role of gravity and mechanical stress on the control and functional adaptation of bone. The results show that significant changes in bone biochemical and biomechanical properties are present after 2 weeks of activity or inactivity in the maturing rat, and these data suggest that immature bone maintains or changes material integrity in response to an optimum stress range.

Future Plans — More recently, we have measured stress-generated electrical currents in normal vitalized bone using a non-contacting current toroid, the former of which are thought to play an important role in maintenance of bone form and in fracture healing. Future studies will examine these stress-generated current potentials in aging, diseased, and fractured bone and bone subjected to different stress environments (hypoactivity and hyperactivity). Examination of growing rat and primate bone biochemical and biomechanical properties will provide additional insight into modeling (cell activation → osteoblastic formation) and remodeling (cell activation → osteoclastic resorption → 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 (exercise) conditions.

Control of Posture

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Purpose — To better understand neuromuscular activity during static balance, we have continued this year to study postural equilibrium in healthy individuals and in patients with neurological disorders. Tests are conducted in our Motion Analysis Laboratory using a force platform to measure postural sway.

Progress — In 1984 we devised a new method for interpreting the data. The fore-aft and the side-to-side displacement of the center-of-foot pressure serve as the X and Y coordinates for a single plot defined as the stabilogram. The standard methods used to interpret stabilograms include visual inspection and the calculation of mean sway amplitudes, mean sway radius, length of sway path, and frequency of sway. Although the standard analytic methods are useful in quantifying the sway path, they contribute little to understanding the motor-control scheme that directs the movements

Future Plans — A new conceptual tool for modeling postural sway is being developed at our center based on the data from stabilograms. We have modified the standard stabilogram software to formulate a simple mathematical model that can be used to describe the data. Unlike previous methods of analysis, our method relies heavily on analyzing the direction and the length of sway path for each coordinate of the stabilogram. We are presently testing our method and the associated mathematical model by re-evaluating previously recorded stabilogram data. We hope to devise a model that has both physical meaning and clinical utility.