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# IX. Biomechanics

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# IX. Biomechanics

## A. Bone and Joint Studies

### Relation of Computerized Axial Tomography (CAT) Scan Mineral Density to Mechanical Properties of Vertebrae

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**Sponsor:** *VA Rehabilitation Research and Development Service and Bioengineering Alliance of South Carolina*

**Purpose**—Previous investigations in our laboratory have studied the correlation between the mechanical properties of vertebral trabecular bone and CAT mineral density measurements and these investigations have shown a high degree of correlation between physically measured parameters and CAT data. The data have not indicated any variation in bone properties with location in the vertebral body. This finding is at variance with the data from at least one other study. The purpose of the present study was to examine the failure modes of vertebral bodies when crushed in a physiologic manner and to correlate the failure data with CAT measurements and with histomorphometric and physical property data.

**Progress**—Vertebral bodies were obtained during routine autopsy at Richland Memorial Hospital and at the Dorn Veterans Administration Medical Center, Columbia, South Carolina. Relevant clinical data such as age, sex, cause of death, radiological and hematological findings, etc. were recorded. As soon as possible after removal, they were radiologically evaluated by CAT scan. Three cylindrical areas within each vertebra were selected for CAT equivalent bone mineral density measurement. Following the radiologic examination, the specimens were frozen at −20 degrees Celsius and held for subsequent mechanical testing.

The mechanical test involves crushing a vertebral body (with posterior elements removed) between "discs" made of silicone rubber in a compression fixture. Measured mechanical properties included load-to-failure and strength. Following the mechanical testing, selected portions of the specimen were embedded, sectioned, stained, and evaluated histomorphometrically. Finally, selected portions of the specimen were used for determination of calcium content by atomic absorption spectophotometry for direct comparison of bone mineral density with the equivalent bone mineral content as determined by the CAT scan.

**Preliminary Results**—As of this date only ten vertebral bodies have been tested and the data are still preliminary. The results show a significant correlation between CAT measured equivalent mineral density, averaged for the whole vertebral body, and breaking load ($R = 0.75$, $n = 10$, $p < 0.03$), between the averaged CAT mineral density and the breaking stress ($R = 0.81$, $n = 10$, $p < 0.02$). The calcium content data and the histomorphometric data are in process.

## Prediction of Trabecular Bone Strength and Modulus by Computerized Axial Tomography (CAT)

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**Sponsor:** *VA Rehabilitation Research and Development Service and Bioengineering Alliance of South Carolina*

**Purpose**—A primary clinical problem which exists today involves the early detection and diagnosis of osteoporosis. Current radiographic techniques have been shown to be relatively insensitive to the degree of skeletal mass loss and no correlations with mechanical properties have been found. The primary objectives of this research were to obtain vertebral bodies at autopsy from normal and osteoporotic individuals, to determine the compressive strength and modulus of the vertebral trabecular bone by mechanical testing, and to correlate the observed mechanical properties primarily with CAT mineral density, but also with calcium content and histomorphometric measurements.

**Progress**—Vertebral bodies were obtained during routine autopsy and radiographically evaluated by CAT scan. Mechanical properties of vertebral trabecular bone were determined by testing cylindrical bone specimens in simple compression to failure. Ultimate strength and elastic modulus were determined directly from load-deformation curves. Atomic absorption spectrophotometry was used to determine weight percent calcium of each specimen, and quantitative light microscopy was used to determine area fraction bone.

**Results**—Significant positive correlations were found to exist between the observed trabecular bone mechanical properties and CAT mineral density. Compressive strength was correlated with both the CAT value ($r = 0.720$, $p < 0.001$) and the squared CAT value ($r = 0.755$, $p < 0.001$). Bone elastic modulus was correlated with both the CAT value ($r = 0.574$, $p < 0.001$) and the cubed CAT value ($r = 0.601$, $p < 0.001$). Trabecular calcium density was also correlated with the CAT value ($r = 0.780$, $p < 0.001$). In addition, a significant positive correlation was found between the CAT value and the area fraction bone ($r = 0.579$, $p < 0.001$).

## Biomechanical Modeling of the Lower Back

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

**Purpose**—A computer model of the lower back musculature is currently under development and will be used to predict the distribution of muscle forces at different levels of the lumbar region under different loading conditions. The biomechanical model is being developed as part of a major research project aimed at studying lower back pain. The project will integrate the biomechanical model described above with myoelectric signal measurement from low-back muscle into a coherent diagnosis of individual muscle dysfunction. The model will also be used to suggest isometric exercises that could selectively activate (or relieve) the affected muscles.

## Dynamic Biomechanics of Spinal Implants

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

**Purpose**—Cyclic, nondestructive, multidirectional testing of three spinal implant systems applied to swine spines and subjected to "physiologic" forces of human magnitude is reported. The ultimate aim and goal is to establish a relative database for comparative *in vitro* testing of spinal implants in current use and develop safer and more biomechanically sound spinal instrumentation.

**Progress**—During the 1986-1987 year, ten swine spines were instrumented with Harrington, Luque, and Drummond implants. Spines were kept hydrated while being tested in a custom-designed, pneumatic powered machine constructed for multidirectional, nondestructive cyclic testing of intact animal and human spines. A thirteen segment spine length extending from T7-L4 was used. The terminal vertebrae were mounted in acrylic in aluminum cups machined for attachment to the upper and lower platins of the machine. Each spine was tested without instrumentation (control), then with a single Harrington distraction rod, paired Luque rods, and Drummond rods. 1677 Newtons (377 pounds) compression and 15 Newton-meters (445 pounds-inch) torsion was simultaneously applied via pneumatic cylinders. The maximum excursion of the axial compression cylinder was set at 1.3 centimeters. Maximum angular displacement of the torsion cylinders was 15 degrees in a clockwise and counterclockwise direction. Off-axis tests were set with the spine positioned at 6 degrees off the vertical neutral axis. Spines were preconditioned for each loading mode to allow for equilibration of the systems, relaxation and warm-up conditioning of the tissues. Radiographs were taken before, during, and after testing. Angular and linear displacements were determined using a photographic method. These spines were also videotaped in the posterior-anterior and lateral projections. A triaxial reference device consisting of three 10 centimeter rods attached to a middle thoracic, lower thoracic, and upper lumbar spinous process was utilized as orthoganal points of reference. These triaxial devices were referenced to 90 degree camera positions and fixed points on the machine. These nine orthoganal points were digitized using the photographs taken in the posterior-anterior and lateral projections. Digitized points were analyzed by a dedicated computer using kinematic techniques. Statistical analysis of the data was then carried out by the Department of Biostatistics.

**Preliminary Results**—Angular and linear displacement data generated during the multiaxis cyclic testing showed that the Drummond and Luque systems were equally resistive to axial compression forces applied to the vertically placed spine and implant systems. Off-axis compression with the spine oriented 6 degrees off the vertical again showed the Luque and Drummond systems to be more stable in lateral bending and angular displacement than the single Harrington distraction rod. The Drummond system appeared slightly more rigid than the Luque rods but this was not statistically significant. During axial torsion at 15 degrees in each direction there was no wire breakage, hook dislodgement, or cut-out. The Harrington hooks were noted to rotate and wobble at bony sites of attachment during cycling. When axial compression and torsion forces were applied simultaneously, both the Luque and Drummond systems resisted angular displacements more than the Harrington distraction rod. Linear displacement measurements revealed similar trends. During simultaneously applied off-axis compression and torsion forces, the Drummond system was slightly more resistant to angular displacement than the Luque system. The Harrington rod was most taxed during this severe testing regimen. It provided no more support than the uninstrumented spine. This was because of bowing of the rod and the relative displacement of the hooks at their insertion sites.

**Future Plans/Implications**—Further multidirectional cyclic testing of posterior and anterior spinal implants is planned for the coming year. Prototypes of anterior fixation devices have been prepared and

are currently in production for *in vivo* and *in vitro* testing.

### Publications Resulting from This Research

**Cyclic Axial Loading of Spinal Implants.** Nasca RJ, Hollis JM, Lemons JE, Cool, TA, *Spine* 10:792-798, 1985.

### Presentations

**Biomechanical Testing of Spinal Implants,** presented to the North American Spine Society, Banff, Canada, June 1987.

**Biomechanical Testing of Spinal Implants,** to be presented to the Federation of Spine Association, February 1988, Atlanta, Georgia.

## Pathokinesiology of Anterior Cruciate Ligament Deficiency

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

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

**Progress**—The knee kinematics of 25 individuals with uninjured knees and of 20 individuals with injured knees have been investigated. The kinematics were quantitated using helical motion analysis. The results of the helical motion analysis reveal clearly that the knee is definitely neither a hinge nor a planar joint. It is a dynamic joint whose kinematic behavior changes over the stride. Statistical analyses were used to compare the kinematics of the injured and uninjured knees and quantitatively define the changes that occur from the loss of the anterior cruciate ligament. These changes are significant. Ligamentous loss results in more adduction and external rotation during certain periods of the stride. Also, the range of translation of the tibia in the medial/lateral direction is reduced and its mean translation is more medial.

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

**Future Plans/Implications**—Presently the data are being analyzed to determine if there is a difference between individuals with tight and loose injured knees. Research is continuing in order to study the effect of corrective procedures and joint prostheses on knee kinematics and muscle function.

### Publications Resulting from This Research

**Helical Motion Analysis of the Knee—I. Methodology for Studying Kinematics During Locomotion.** Shiavi R, Limbird T, Frazer M, Stivers K, Strauss A, Abramovitz J, *Journal of Biomechanics* 20(5):459-469, 1987.

**Helical Motion Analysis of the Knee—II. Kinematics of Uninjured and Injured Knees During Walking and Pivoting.** Shiavi R, Limbird T, Frazer M, Stivers K, Strauss A, Abramovitz J, *Journal of Biomechanics* 20(7):653-665, 1987.

## Effect of Ligamentous Instability on Knee Joint Proprioception

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

**Purpose**—The purpose of this project is to test the hypothesis that anterior cruciate ligament injured knees have impaired proprioception perception that may contribute to accelerated deterioration of these knees.

We propose to measure proprioception in two ways. The first is to test the ability of a patient to reproduce a given position of the lower leg in space. The second is to test the patient's ability to perceive motion at the knee controlling position, velocity, acceleration, and the rate of change of acceleration (jerk).

**Progress**—Angular motion at the knee can be measured by measuring displacement at the ankle if the length of the leg is known. The angle is equal to 2 times the distance the angle moves, divided by the distance from the center of rotation of the knee to the ankle.

A transmitter that outputs the sound of a known wavelength and a reference light signal is placed on the ankle. The phases of the sound and light signals can then be compared. As the ankle moves toward the receiver, the phase of the sound advances relative to the phase of the reference light signal. Using ultrasound at 40 KHz and measuring the phase to 0.05 Hz, it is possible to measure relative motion between the transmitter and receiver at 0.5mm. As most tibias are approximately 40 centimeters long, this permits measurement of motion at the knee in a noncontact fashion with an accuracy of about 0.12 degrees.

**Preliminary Results**—Two transmitters and two receivers, including phase comparators, counters, and position displays, are complete and working. Mechanical supports and partitions, which serve to separate the signals from the injured, and a control normal knee that serves to support the positioning motors are complete. Stepping motors which will be able to control the position of the ankle with a precision of 0.001 of an inch are purchased. The stepper motor drivers are yet to be completed.

## Study of Bone Structural Response to Altered Loading

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

**Purpose**—The objective of this research is the study of mechanically-induced adaptive bone response with the focus upon development of patient-specific, analytic, predictive models and noninvasive imaging techniques. Three-dimensional finite element models automatically generated from CT scan data will be used to predict bone remodeling along principal stress directions, according to Wolff's Law. Theoretical results will be compared with actual bone remodeling obtained from histology.

**Progress**—A two-dimensional finite element analysis indicated core drillings in a canine femur would cause altered principal stress directions and result in bone remodeling. Such drillings were performed and the results were monitored for nine months with CT scans. Histology of the retrieved hips will establish the actual remodeling and permit verification of our finite element predictions as well as our noninvasive histomorphometry technique.

To determine the three-dimensional *in vivo* stress distribution, digital image processing software was developed. The software automatically extracts bone geometry, density, and microstructural orientation from the serial CT scan. To create the finite element model, eight-noded "brick" elements are automatically generated according to the bone geometry. Mesh density is user-specified. The elastic modulus

is variable throughout the model and is determined by using quantitative computed tomography and a density-modulus relationship. Inclusion of microstructural orientation in the model is under investigation.

*In vitro* evaluation of bone contour extraction and microstructural identification software were tested using an excised vertebra. Trabecular spacing, area fraction of bone, and orientation angle were calculated using thresholded CT scans and CT images enhanced with software developed as part of this study.

**Results**—Densification of cancellous bone surrounding the core drillings is apparent. Quantitative verification of finite element model predictions await histologic sectioning now being performed. Comparison of image processing results for the vertebrae with calculations made from histologic sections verifies that the enhanced imaging is less sensitive to display setting than thresholding; and significantly improves the accuracy of calculated trabecular spacing and area fraction of bone. Preliminary inspection of the automated finite element analysis indicates qualitative results consistent with previous finite element models generated by hand. Further analysis and testing is necessary for verification of quantitative results.

**Future Plans/Implications**—Results of this study will be applied to study patient-specific fracture risk and prosthesis design. The automated finite element modeling technique also can be adapted to model other tissues and objects which can undergo CT scanning.

## Bone In Vivo and In Vitro Stress and Strain Patterns

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

**Purpose**—The objective of this research was twofold: to test the hypothesis that "bone models/remodels during growth and altered activity in order to maintain an optimal state of strain," and to determine the level of activity necessary to maintain or augment normal bone strength.

**Progress**—Immature (3- to 17-week-old) and adult rats were subjected to normal, hypoactivity (bedrest, paralysis, simulated weightlessness) and hyperactivity (voluntary and involuntary exercise) regimens. Bone stress and strain patterns were recorded from the femur at mid-diaphysis *in vivo* (gait) and *in vitro* (static and dynamic mechanical tests). Histomorphometric and biochemical analyses of the femur cross section were also conducted.

**Results**—In the normal rat, a two-fold increase in both bone geometric and material properties resulted in a four-fold increase in bone structural properties (strength) during growth, which was followed by a greatly reduced rate of change in the adult. No changes in the *in vivo* strain, stress or resultant moments were observed during growth or in the adult and the ratio of torsional strength to *in vivo* load (torsional safety factor, ST) remained constant (ST = 12). Hypoactivity resulted in a significant reduction in bone geometry, which was partially compensated by an increase in bone calcium content, but overall the bone strength was significantly reduced. Hyperactivity (0.02 to 4.0 kilometers/day running at 11.2 meters/minute), however, did not significantly alter bone geometric, material or structural properties beyond that of normal growth. An activity "window," therefore, is hypothesized to exist below which reduction in bone properties occurs and above which an increase in bone properties is predicted to result. The loads imposed by moderate activity (running at 11.2 meters/minute, 0.005 peak strain/second) do not appear to augment bone geometry, material or structure.

**Future Plans**—Our plans for the immediate future are to correlate the appendicular bone mineral content (BMC) in athletes to level of activity. Three groups of athletes will be examined: 1) high intensity, short duration (weight lifting); 2) medium intensity, medium duration (sprinting); and, 3) low intensity,

long duration (running). The BMC will be correlated to the workout intensity in order to identify the load threshold necessary to stimulate a positive osteogenic response. In addition, we are planning to examine the normal and pathogenic response of the lumbar spine to vibration and other loading modes in an effort to assess mechanical factors involved in low back pain.

**Publications and Awards Resulting from This Research**

**Fatigue of Immature Baboon Cortical Bone.** Keller TS, Lovin JD, Spengler DM, Carter DR, *J. Biomechanics* 18:297-304, 1985.

**Geometric, Elastic, and Structural Properties of Maturing Rat Femora.** Keller TS, Spengler DM, Carter DR, *Journal of Orthopaedic Research* 4:57-67, 1986.

**The Effects of Simulated Weightlessness on Bone Biomechanical and Biochemical Properties in the Maturing Rat.** Abram AC, Keller TS, Spengler DM, *J. Biomechanics,* (in press).

**Biomechanical Response of Immature Bone During Voluntary Exercise.** Keller TS, Harris NL, Spengler DM, *Calcif. Tissue International,* (in press).

**Regulation of Bone Stress and Strain in the Immature and Mature Rat Femur.** Keller TS, Spengler DM, *J. Biomechanics,* (in press).

**1986 National Student Research Forum Physical Medicine and Rehabilitation- Education and Research Foundation Award in Physical Medicine and Rehabilitation,** A.C. Abram.

**1987 National Student Research Forum Physical Medicine and Rehabilitation-Education and Research Foundation Award in Physical Medicine and Rehabilitation,** N.L. Harris.

**1987 American Society of Biomechanics Predoctoral Award,** T.S. Keller.

## Biomechanical Testing of Spinal Instrumentation Systems

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**Sponsor:** *AcroMed Corporation, Cleveland, OH*

**Purpose**—A variety of instrumentation systems are available today and new ones are being developed for the purpose of stabilizing single or multiple spinal levels in the lumbar and lumbosacral region. The primary goal of an instrumentation system used in surgical stabilization of spinal segments is to share the loads acting on the spine until a solid biologic fusion has taken place. The ability of a spinal instrumentation system to meet this goal can be evaluated by quantifying the failure load and rigidity of the construct under physiologic loading conditions. The goal of this study is to perform biomechanical evaluation of these instrumentation systems under static as well as cyclic loads.

The specific objective of the study is to perform comparative evaluation of two instrumentation systems for single segment stabilization. These are: the Variable Screw Placement (VSP) Spine Plate, and the PDC Clamp.

**Progress**—The test apparatus has been fabricated and initial studies are being performed to evaluate the accuracy and reproducibility of the measurement system. Samples of the two instrumentation systems will be tested to quantify the following characteristics of each: 1) failure strength and rigidity (load-deformation characteristics) of the construct under static loading; 2) ridigity of the construct following repeated application of loading cycles; and, 3) fatigue life of the construct.

## Evaluation of the Slide Board Exercise for Anterior Cruciate Ligament Rehabilitation

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**Sponsor:** *The Cleveland Clinic Research Foundation*

**Purpose**—The slide board exercise is used clinically for the rehabilitation of patients with anterior cruciate ligament (ACL) reconstructions. It involves sliding side-to-side, in a speed-skating motion, over a low-friction surface. This weightbearing exercise may avoid the impact loading of walking, running, and jumping rope. It enforces co-contraction of the quadriceps and hamstrings in a safe range of motion

of the knee, and should improve balance and coordination. Properly designed, the portable slide board platform is an inexpensive device suitable for patients' use at home. The goal of this study is to assess the potential for injury from varus or valgus moments on the collateral ligaments of the knee at push-off from, or collision with, the slide board bumpers.

**Progress**—A slide board has been constructed on a wooden platform using a 2-foot by 8-foot sheet of Marlite™ with padded bumpers at the ends. This slide board was instrumented with two AMTI force plates, one to measure the vertical force at the point of foot-bumper contact and the other to measure the lateral force of collision. This data is transmitted through A/D converters into a microprocessor and manipulated for immediate display, with hard copies for permanent patient record.

**Results**—Data acquired in preliminary tests have shown that the vertical force exceeds body weight at contact, then decreases below body weight, while the lateral force ramps to a maximum during push-off, and then rapidly decreases to zero after separation from the bumper. EMG data verifies simultaneous contractions of the quadriceps and hamstring muscles during this exercise, lending stability to the joint and minimizing tension on the reconstructed ACL.

These test results will provide a quantitative assessment of patients' progress in rehabilitative therapy. In addition, the test results may be used to evaluate differences in velocity, stance, bracing, and training. Possible or necessary changes in the design of the exercise platform can also be evaluated.

## Biomechanical Testing of a New Anterior Construct for Segmental Spinal Fusion

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**Sponsor:** *Howmedica*

**Purpose**—The use of a posterior interbody fusion is a well recognized technique in stabilizing a spinal segment in the surgical treatment of low-back pain. However, potential problems often arise in using this technique due to difficulty in incorporating bone grafts, resorption of the graft, a lack of anterior support, and potential additional morbidity in procurement of the graft. The overall purpose of this study is to evaluate the efficacy of a porous-coated insert as an anterior fusion construct for low-back pain surgery.

The specific objective of this study is to evaluate the mechanical stability of spinal segments under physiologic loads following implantation of the fusion construct in a baboon model.

**Progress**—To date, 11 baboon spines have had segmental destabilizations to serve as a control group for evaluation of the implant. From this group, three were used to study the installation system, and eight were retained for actual biomechanical testing of the operated segment. In addition, 12 baboon spines have had procedures performed to install the test implant in conjunction with surgical segmental destabilization. Six of these specimens have been selected for the 6 week postoperative study group, and the remaining six will be sacrificed for 12 weeks postoperatively. All baboon specimens have had anterior-posterior radiographs, and lateral radiographs in flexion and extension prior to any given procedure. Immediately postoperatively, the specimens with implants have had additional A/P and lateral X-rays taken. Lastly, prior to sacrifice, all specimens have had a final set of radiographs taken with three views, as in the initial set.

**Future Plans**—The next phase of this study will involve analysis of the mechanical stability of the harvested baboon specimens. This step will involve measurement of the load-deformation properties of individual spinal segments in flexion-extension, lateral bending, and torsion. These tests will be performed on specimens consisting of shams, and those with implants.

## Knee Biomechanics of Athletes with High Risk Exposure to ACL Injury

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**Sponsor:** *LSU Department of Orthopaedics*

**Purpose**—The objective of this study was to identify specific sports activities that may render the athlete at high risk to ACL injury, and to outline the appropriate preventive exercise to be used as an adjunct to such activity.

**Progress**—It was shown that athletes participating regularly in sports such as basketball, volleyball, or resistive exercises which routinely utilize the quadriceps over and above the frequency of use of the hamstrings, develop low and inhibited coactivation of the hamstrings during knee extension. This exposes the joint to weakened resistance to injury. Athletes, such as triathlon participants, who utilize their hamstrings regularly, have normal coactivation of the hamstrings and thus lower exposure risk to injury.

**Preliminary Results**—It is suggested that athletes with muscular imbalance engage in adjunct hamstring exercise before or after their chosen sport to reduce their high risk exposure to knee ligament injuries.

## Biomechanics and Electromyography of Anterior Cruciate Ligament (ACL)-Deficient Knees

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**Sponsor:** *LSU Department of Orthopaedics*

**Purpose**—The objective of this study was to identify the biomechanics and electromyography patterns associated with knee instability due to ACL deficiency, and to develop a noninvasive, reliable methodology for diagnosis as well as rehabilitation modalities to be used as alternatives or adjuncts to current procedures.

**Progress**—Findings to date show that a reflex arc exists from ACL receptors to the hamstrings and, upon overloading of the ligament, the arc is triggered on to provide muscular assistance in preventing damage to the ligament. Furthermore, in the absence of the ACL due to trauma, receptors from the joint capsule or muscles perform the same function such that joint stability is preserved (*American Journal Sports Medicine*, May, 1987). Hamstrings exercise therapy was clearly shown to be a proper rehabilitation modality.

## Quantification of Mobility Performance for Functional Assessment, Diagnosis, and Therapy of Neuromuscular, Skeletal, and Synovial Joint Dysfunctions

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**Sponsor:** *National Institute on Disability and Rehabilitation Research; National Science Foundation; VA Rehabilitation Research and Development Service*

**Purpose**—Functional assessment of disabling mobility and manipulation pathologies requires reliable means for quantitatively documenting the kinematic and dynamic state of the movement-impaired individual. Such capability can establish the effectiveness of surgical and/or rehabilitative procedures. This project involves an assessment process that goes beyond documenting the current status of the patient.

Computer-Aided Surgical Simulation (CASS) is a

computer-based system whose antecedent was Computer-Aided Design (CAD). These techniques, when applied to musculoskeletal defects will provide the medical practitioner with a computer-graphics display of the patient's anatomy, on which a tentative therapeutic procedure can be implemented.

When representations of the patient's musculoskeletal anatomy in the computer database are altered by the simulated intervention, the computer displays the effect on the patient's posture, mobility, joint range-of-motion, etc. The medical practitioner can then compare the original state of the movement capability of the patient, acquired via a movement analysis system, with the changes that would occur if the simulated procedure were actually performed. The physician or therapist would then be free to alter or optimize the proposed procedure until satisfied or perhaps abandon it prior to actual surgical or therapeutic intervention.

The project is subdivided into four tasks: mobility analysis; patient-specific anatomical representation; individual muscle activity determination; physician/computer interfacing.

**Progress**—The electro-optical camera-based, TRACK software systems at the Newman Laboratory at MIT and the Biomotion Laboratory at Massachusetts General Hospital are being used to acquire kinematic and dynamic patient data relevant to the study. The hospital location of the MGH system facilitates its primary use for patient studies while the MIT system serves as a test bed for research enhancement.

Among the clinical studies at MGH pertinent to this project, the subject with the prosthetic femoral head that senses pressure at 10 locations on her acetabular cartilage continues as a source of novel data for more than 3 years now. She is fully recovered and has a completely normal, pain-free, and functional hip. The instrumentation in the prosthesis also continues to perform flawlessly. The stabilization over time of the peak-pressure values measured during normal movement tasks is providing quantitative information on the recovery time of the musculoskeletal system following major hip surgery. Whereas pressures in normal level walking had stabilized by the end of the first year postoperatively, stair climbing data stabilization required several more months, and it was fully a year and a half before stable values occurred in the highest pressure producing movement, that of rising from a low chair without arm assist. This new information provides, for the first time, a quantitative assessment of the mechanical state of the human hip joint during the entire process from surgery to full normal performance.

The hip pressure data, in particular the magnitude and orientation of the peak pressures during stair-climbing and rising from a chair, implicated the co-contraction of major muscle groups about the joint. The pressures measured could not otherwise be reconciled with the kinematic and dynamic analyses based on the TRACK data. To explore this hypothesis, multiple muscle EMG recording was added and synchronized with the prosthesis pressure, TRACK kinematic, and forceplate data. The new muscle information confirms the co-contraction hypothesis. Dynamic studies estimating joint forces from gait analysis records must recognize that such co-contraction augments the force the joint experiences but that cannot be discerned from the kinematic and forceplate data.

The novel pressure data from this one subject must, of course, be supplemented by information from a larger patient population. A contract from the Veterans Administration Rehabilitation Research and Development Service to the Veterans Administration Medical Center in Jamaica Plain, Boston, is supporting the assembly, test, and implantation of up to six additional pressure-instrumented prostheses. Experience with technical aspects of the first implant will influence the design of subsequent devices.

A second clinical study at the MGH Biomotion Laboratory exploited their bilateral TRACK capability in a comparison of body center-of-pressure, as measured on the two forceplates, versus determination of the body center-of-mass based on the kinematics of an 11-segment model of the human including the extremities, the trunk, and the head. The technique was developed using normal subjects and is being applied on a population of cerebral palsied children.

The research effort at MIT completed improvements in TRACK calibration techniques, axis of rotation determination, and data processing including comparisons of filtering versus smoothing, and axis-of-rotation determination. Research and development continued on the large-volume TRACK system that will provide quantitative movement information over multiple strides, during unstruc-

tured mobility such as in the simulation of electronic travel aids for visually-impaired persons, or to study the controllability of powered wheelchairs.

**Patient Specific Anatomical Representation.** Computer tomographic (CT) and magnetic resonance imaging (MRI) two-dimensional scan data provide quantitative information for two aspects of the computer-aided surgical simulation system.

First, dynamic force estimations using TRACK kinematic data in Newton's equations require the mass and inertial properties of the individual limb and body segments. The traditional approach of scaling such data from cadaver measurements on very limited and homogeneous populations is inappropriate here, since the system data must be specific to the particular patient whose physiognomy is frequently abnormal. Research comparing estimates of segment inertial properties computed from the scans with direct physical measurements of the same cadaver segments have confirmed the feasibility and accuracy of automatic estimation of segment parameters based on CT or MRI scans.

The CT or MRI scans are also used to generate color graphic displays of the patient's anatomy on which the simulated procedure is conducted. Major efforts this past year have focused on database design and data processing techniques to reduce computation and memory requirements necessary to construct and manipulate three-dimensional representations of anatomy generated from contiguous series of two-dimensional scans.

**Individual Muscle Activity Determination.** The musculoskeletal effort in support of the Computer-Aided Surgical Simulation program is now supported under a National Science Foundation grant, the progress report of which is presented elsewhere in this Journal.

**Physician/Computer Interfacing.** By education and experience, physicians traditionally employ visually acquired information as contrasted with the mathematical descriptions used by engineers. Since all data in the computer is number-based it must be presented to the medical practitioner in familiar visual form. Thus our computer graphics must employ and exploit, in a natural fashion, the inherent knowledge and skills of the surgeon or therapist without imposing new, additional training burdens. Although much technique can be adapted from the now well-established field of computer-aided design, including the use of graphic windows, menus, pointers, and cursor and mouse-control, certain aspects of graphic manipulation in surgical simulation are quite different from what is encountered in engineering design. Natural anatomical objects are far more amorphous and complex in shape than the more regular prismatic and curvilinear engineering objects. Furthermore, engineers usually develop a device *de novo*, building element upon element, whereas in surgical simulation the bone shape, for example, must be presented as it is and techniques must be developed for permitting the simulation of alteration, as for example, in intertrochanteric osteotomy. A major effort this past year has developed the data structure and graphic interactive techniques for performing such "cutting" and "glueing" techniques, simulating the severing of bone and the subsequent natural biological reconnection process.

**Publications Resulting from This Research**

**Determination of Body Segment Inertial Properties.** Brown GA, Tello RJ, Rowell D, Mann RW, *Proceedings, RESNA 10th Annual Conference*, San Jose, CA, 1987.

**Determination of Body Segment Parameters Using Magnetic Resonance Imaging.** Brown GA, Tello RJ, Rowell D, Mann RW, *9th Annual IEEE EMBS Conference*, Boston, MA, November 1987.

**Determination of Body Segment Parameters Using Computerized Tomography and Magnetic Resonance Imaging.** Brown GA, Tello RJ, Rowell D, Mann RW, *ASME Winter Annual Meeting*, Boston, MA, December 1987.

**A Precision PAM-FM Multichannel Implantable Patient-Monitor Telemetry System.** Burgess RG, Mann RW, *9th Annual IEEE EMBS Conference*, Boston, MA, November 1987.

**Investigation of In Vivo Loading Rate Characteristics in a Human Hip Joint.** Carlson KL, Hodge WA, Fijan RS, Mann RW, Harris WH, *Proceedings RESNA 10th Annual Conference*, San Jose, CA, 1987.

**Transmission of External Force Pulses Across the Human Hip Joint.** Carlson KL, Rogers LL, Hodge WA, Mann RW, *ASME Winter Annual Meeting*, Boston, MA, December 1987.

**Arising from a Chair: The Role of Bi-Articular Muscles in Resolving Lombard's Paradox.** Catani F, Hodge WA, Mann RW, *9th Annual IEEE EMBS Conference*, Boston, MA, November 1987.

**Hip Dynamics in Level Walking, Stair Climbing and Rising from a Chair.** Catani F, Hodge WA, Mann RW, *ASME Winter Annual Meeting*, Boston, MA, December 1987.

**The Role of Co-Contraction During Human Movement.** Catani F, Hodge WA, Mann RW, *ASME Winter Annual Meeting*, Boston, MA, December 1987.

**Estimation of Camera Positions and Orientations Using a Control Distribution of Unknown Relative Geometry.** Fijan RS, Mansfield PK, Mann RW, *ASME Winter Annual Meeting*, Boston, MA, December 1987.

**Human In Vivo Acetabular Pressure Measurement: A One-Year Update.** Hodge WA, Fijan RS, Carlson KL, Riley PO, Mann RW, Harris WH, *Transactions of the 32nd Annual Meeting of the Orth. Research Society*, 11:436, 1986.

**Contact Pressures in the Human Hip Joint Measured In Vivo.** Hodge WA, Fijan RS, Carlson KL, Burgess RG, Harris WH, Mann RW, *Proceedings of the National Academy of Sciences,* USA 83:2879-2883, May 1986.

**Hip Dynamics in Star Climbing and Rising from a Chair Following Hip Arthroplasty.** Hodge WA, Zimmerman S, Riley PO, Mann RW, *Proceedings, RESNA 10th Annual Conference,* San Jose, CA, 1987.

**The Influence of Hip Arthroplasty on Stair Climbing and Rising from a Chair.** Hodge WA, Zimmerman S, Riley PO, Mann RW, *ASME Winter Annual Meeting,* Boston, MA, December 1987.

**Interpreting Femoral Head Pressure on Natural Acetabular Cartilage In Vivo Via Gait Analysis.** Mann RW, *Proceedings, Second Annual East Coast Clinical Gait Laboratory Conference,* Philadelphia, PA, November 1986.

**Rehabilitation Implications of In Vivo Hip Pressure Measurements.** Mann RW, Carlson KL, Burgess RS, Fijan RW, Hodge WA, Harris WH, *Proceedings, RESNA 9th Annual Conference,* Minnesota, 201-203, June 1986.

**Internal Calibration of Opto-Electronic Cameras.** Mansfield PK, Fijan RS, Mann RW, *9th Annual IEEE EMBS Conference,* Boston, MA, November 1987.

**Opto-Electronic Camera Image Plane Calibration.** Mansfield PK, Fijan RS, Mann RW, *9th Annual IEEE EMBS Conference,* Boston, MA, November 1987.

**A Comparison of Smoothing and Digital Filtering/Differentiation of Kinematic Data.** Murphy M, Mann RW. *9th Annual IEEE EMBS Conference,* Boston, MA, November 1987.

**Evaluation of Posture and Balance in Cerebral Palsied Children.** Riley PO, Hodge WA, Gould A, Ehrlich M, Harris WH, Mann RW, *Proceedings, RESNA 10th Annual Conference,* San Jose, CA, 1987.

**Center of Gravity Estimation Technique in the Study of Postural Control.** Riley PO, Hodge WA, Mann RW, *ASME Winter Annual Meeting,* Boston, MA, December 1987.

**Determination of Joint Centers for Posture Studies.** Riley PO, Fijan RS, Hodge WA, Mann RW, *ASME Winter Annual Meeting,* Boston, MA, December 1987.

**Generation of Surface Anatomy from CT MRI Images.** Tello RJ, Chang G, Mann RW, Rowell D, *Proceedings, RESNA 10th Annual Conference,* San Jose, CA, 1987.

**Comparison of Finite Helical Axis Estimation to Instantaneous Helical Axis from Noisy Kinematic Data.** Van der Meulen MC, Murphy MC, Mann RW, *Orthopaedic Research Society Conference,* Atlanta, GA, February 1988.

## Segmental Bone and Joint Replacement after Tumor Resection

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**Sponsor:** *National Institutes of Health*

**Purpose**—The emerging advances in adjuvant therapies for malignant bone and soft tissue tumors and the introduction of a surgical staging system to rationalize the extent and margin of tissue resection have renewed the interest in limb-saving procedures. The use of prosthetic implants based on the most advanced biomechanical design concepts and new implant materials appears to be very promising, not only providing useful limb function for curable cancer patients, but also as a palliative treatment benefiting those with metastatic lesions. Two systems of metallic tumor prostheses were developed, but our clinical and laboratory results have demonstrated significant residual problems associated with these devices.

The currently proposed renewal is to achieve the following specific aims: 1) to develop a new non-porous-coated modular tumor prosthetic system; 2) to modify the previous porous-coated modular prosthetic system and to examine the efficacy of extracortical fixation through bony ingrowth; 3) to investigate the adjuvant therapy effects on tissue incorporation into the porous implant; 4) to develop a method to attach soft tissue to the prosthesis; 5) to correlate patients' clinical assessment results with their biomechanical functional evaluation results; and, 6) to develop booklets for better patient home care and to write instructional manuals describing surgical techniques involving these prostheses.

Bone geometric study and theoretical and experimental stress analyses will be performed to optimize the design of the modular systems. Dogs will be used as the models to investigate the biological, functional, and adjuvant therapy effects on prosthesis fixation through radiographic, histologic, and biomechanical analyses of the specimens. Established objective functional evaluation methods and techniques will be used to study the patient's functions and correlate them with the clinical assessment criteria proposed by Dr. W. Enneking. We plan to initiate a multi-institutional trial program after the new prosthetic systems are developed and tested.

The long-term objective is to perfect two segmental bone/joint prosthetic systems which can be safely used on the majority of the patients with resectable primary tumors for restoration of function and those

with metastatic lesions for palliative purposes. These devices can also be used effectively in general orthopedic surgery for limb salvage in the treatment of trauma, infection, metabolic bone disease or failed joint arthroplasty cases with extensive bone loss.

## Biomechanics of Metastatic Defects in Bone

**Wilson C. Hayes**
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**Sponsor:** *National Institutes of Health*

**Purpose**—Advances in the palliative treatment of patients with established metastatic malignancies have not only prolonged patient survival but also increased the incidence of bony metastases and subsequent pathological fractures. Thus, the prevention and effective treatment of fractures associated with metastatic defects in bone has become an increasingly important aspect of the care of cancer patients. Unfortunately, only the crudest of clinical guidelines are currently available which may be used to assess the increased fracture risk associated with metastatic lesions in bond. Therefore, the appropriate time for prophylactic stabilization of impending fractures is not known.

This investigation will be directed in the long-term to the development of comprehensive biomechanical guidelines for the orthopaedic assessment and treatment of metastatic defects in long bones, the proximal femur, and the spine. A four-phase, staged approach will be used. In Task I we will conduct retrospective radiographic reviews of patients exhibiting metastatic lesions in those regions and determine the most frequent sites and approximate shapes of the lesions. As part of this task, we will also develop improved diagnostic imaging procedures for the description of lesion geometries. In Task II, we will determine *in vitro* the strength reductions associated with simulated defects in long bones, the proximal femur and the spine. In Task III we will use finite element modeling of defects in these regions to provide a theoretical framework for interpreting the experimental results and assessing the sensitivity of the fracture risk predictors to individual patient variations. In Task IV we will combine these findings by developing structural predictors of fracture risk for individual patients with particular lesions. Biomechanical guidelines appropriate for each skeletal region will be developed and tested retrospectively in clinical populations. These guidelines should represent a significant improvement in the orthopaedic care of patients with metastatic defects in bone.

## A Comprehensive, Quantitative, Predictive Model of the Human Knee Joint

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**Sponsor:** *National Science Foundation*

**Purpose**—The knee is the largest, most complex, and most frequently injured of the synovial joints in the human body. Subject to highly complex loading, especially in single-leg support, in athletics, and in unexpected falls, it is also susceptible to externally induced trauma due to the absence of thick, soft, surrounding tissue such as cushions the hip. Knee injuries frequently culminate in permanent debilitation and may lead to osteoarthritis and the need for consequent replacement by artificially implanted joints.

Prevention and treatment of injuries could be improved by better knowledge of the kinematics and dynamics of the normal and pathological knee, by better defining of the contributions of the passive constraints (the cartilage surfaces and menisci and ligaments) and by better understanding the roles of the active constraints (the 15 muscles that act across the knee joint, 12 of which are biarticular with either the hip or the ankle).

This project is developing a comprehensive, mathematically expressed, computer-manipulable model of the human knee joint with which to calculate the kinematics and dynamics of the normal knee. Then, following adequate verification, we will employ the model to simulate the consequence of specific losses observed in the pathological knee—thereby leading to a better understanding of preventive and treatment modalities. The understanding of the normal and pathological knee derived from the model is also expected to contribute to the specifications for improved total knee replacement prosthesis.

**Progress**—The emphasis during this project year has been on defining the three-dimensional movement volume that is constrained by passive structures in the knee—the articular cartilage surfaces, the menisci, and the ligaments. This passive movement volume is subsequently further influenced by the action of muscles, the forces of which cross the knee articulation.

The new ultrasonic machine for scanning the complex geometry of the knee articular architecture neared completion. The software previously developed for hip geometry measurement was transferred to a new personal computer. A study of the feasibility of determining the structural properties of the menisci using optical measurement techniques was undertaken. Most of the physical property data in the literature concern ligaments that apply loads that cause failure. These are inappropriate for our study: during normal knee activity, the stress and strain experienced by the ligaments is far less. Accordingly, techniques are being developed to measure stress and strain in ligaments at physiologically relevant levels. New techniques include methods for measuring ligament cross-section in order to establish the stress state and for determining the physiological "resting" length in order to quantify strain.

The experimental data to be used to validate the mathematical model of the knee passive structures are our unique *in vivo* bone movement data. The LED arrays used to acquire this TRACK kinematic information were mounted on bone pins inserted in the femur and tibia of a human volunteer. Since that experiment is not easily reproduced, current studies are comparing data from external arrays (mounted noninvasively) with the bone pin data. A significant advance in the quality of time derivatives of TRACK position and orientation data was achieved through a comparative study of filtering versus smoothing of the kinematic data.

During dissection of human cadaver limbs used on other laboratory projects, the TRACK system is being used to quantify and record the geometry of the origins and insertions of the ligaments and muscles. Generalized musculoskeletal models of the lower limb developed earlier in this laboratory, are being refined and specialized to the specific subject via this anatomical mensuration technique.

**Publications Resulting from This Research**

**A Comparison of Smoothing and Digital Filtering/Differentiation of Kinematic Data.** Murphy MC, Mann RW, *9th Annual IEEE EMBS Conference*, Boston, MA, November 1987.

**Comparison of Finite Helical Axis Estimation to Instantaneous Helical Axis from Noisy Kinematic Data.** Van Der Meulen MC, Murphy, MC, Mann RW, *Proceedings of the 34th Annual Meeting, Orthopaedic Research Society*, Atlanta, GA, February 1988.

## Biomechanics of Joint Motion

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**Sponsor:** *National Science Foundation; LSU Department of Orthopaedics*

**Purpose**—A systematic approach was designed to study the biomechanics of joint motion, including the various anatomical structures associated with the knee and elbow: bones, ligaments, antagonistic muscle pair, articular surface, receptors, and their complex sensor-motor control drive.

**Progress**—Several important developments have been found so far, including the fact that the antagonist muscle is always active at a distinct but low level during isometric and slow isokinetic movements. At maximal voluntary effort, the antagonist EMG is inversely released to its moment arm about the joint,

thereby exerting a constant opposing torque to the motion. Furthermore, when flexion-extension movements are performed vertically (to ground), the antagonist EMG compensates for the impact of the gravity vector on the limb mass, and the effective moment arm length changes from the mass centroid to the joint.

**Preliminary Results**—The conclusions so far indicate that the antagonist muscle compensates for various internal and external "disturbances," aiming to maintain joint and motion stability.

## Kinematics of the Ankle and Subtalar Joint

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**Sponsor:** *Natural Sciences and Engineering Research Council of Canada*

**Purpose**—The objective of this research project is to develop an analytical tool (model) and technique from which the pattern of motion, occurring at the ankle and subtalar joint, can be quantitatively described. More specifically the objectives are:

1) To determine from 15 amputated lower limbs, the direction vectors of the axis of rotation at: a) the ankle, for the movement ranging from 40 degrees plantarflexion to 20 degrees dorsiflexion and back; b) the subtalar joint, for the movement ranging from 10 degrees eversion to 20 degrees inversion and back. It is hypothetized that the following equations related to body kinematics can be applied to described foot and ankle movements: a) circular motion (fixed axis of rotation), b) euler transformations (fixed center of rotation, spatial rotation), c) screw matrix (instantaneous center of rotation, spatial rotation and translation).

2) To determine the relationship between a noninvasive technique (using surface markers) and an invasive technique (using osseous markers) for spatial data acquisition. Once the noninvasive technique has been validated, it could be used *in vivo* to assess foot ailments, sprains and rheumatoid feet. Therefore, physiotherapists, orthopaedic surgeons and orthotists, as well as prosthetists, would have a clinical tool for the assessment and treatment of pathological conditions of the ankle and subtalar joint. A better understanding of the kinematics of the ankle and subtalar joint could be helpful in the design of external and internal prostheses as well as orthoses.

This technique could also be used to assess the pattern of motion with the use of different footwear, such as shoes and construction work boots; and sport footwear, such as running shoes, track shoes, and skates.

## Ground Reaction Torque and Subtalar Joint Function

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**Sponsor:** *Science and Engineering Research Council*

**Purpose**—It has been suggested that direct measurement of the torques occurring at the foot-ground interface may yield useful information regarding the efficiency of the "torque-converting" action of the foot/ankle and subtalar joints and hence may provide useful diagnostic information on the pathologies of these articulations. Although this data, as measured using a standard force platform and commonly known as the "Mz" trace, has been briefly mentioned in a number of general studies on the force platform, apparently little attention has been paid to it in relation to foot function and hence there is little normative data available.

**Progress**—The torque (Mz) about the vertical axis was obtained for a group of 20 normal, symptom-free subjects walking barefoot at their own preferred speed across a standard Kistler force platform. Side

and rear view video recordings of each test were analyzed to obtain basic temporal-distance parameters, and an estimation of the degree of ankle inversion/eversion during the stance phase of gait.

A total of five torque traces were obtained for each leg of each subject. Each trace was then normalized to body weight and mean data traces for each leg calculated using a Fourier analysis technique. Two further subjects were tested on five separate occasions to check the method for repeatability. Additionally, a small group of pathological subjects have been tested.

**Preliminary Results**—Although the principal features of the normal data could be identified in relation to function, considerable intra- and inter-subject variations, both in magnitude and shape, were apparent.

*Intra-subject variation*—Despite variability in magnitude, it is apparent that the principal features of the data traces are common; that is, the basic pattern of the data is constant and that each trace may be broken down into three distinct parts corresponding to the three phases of stance. This subjective repeatability was also observed in the data obtained from all normal subjects, and within the data obtained from tests carried out on the two subjects used for the repeatability study. However, much greater variation was observed between subjects.

*Inter-subject variation*—The major difference between subjects occurs in the second phase of stance, between foot flat and heel-off, and represents a shift of the curve about the zero torque axis. It was postulated that variations from zero torque in this region of the curve would be the most sensitive indicator of abnormal function, and therefore a small group of subjects with known subtalar deficiency have also been tested. Although these results tended to corroborate the assumption of zero "normal" torque, they were all well within the extremes of the normal group data. However, the subjects with pathology were all active and presented with symptoms associated with activity, suggesting the possible presence of "sub-clinical pathology" within the more sedentary members of the normal group.

In comparison with alternative kinematic techniques, the measurement of torque to assess subtalar joint and foot function is a relatively easy task. The data obtained has shown that significant torques are generated throughout the stance phase of gait, and has been found to be sufficiently sensitive to indicate both intra- and inter-subject differences within the normal sample group.

**Future Plans/Implications**—The initial results of a further preliminary study on a group of early post-treatment ankle fracture patients have proven encouraging, although problems associated with pain compensation have been noted. However, we feel there is justification for further work along these lines.

## Biomechanical Evaluation of the Patellofemoral Joint Under Various Degrees of Fixed Rotational Deformities of the Femur

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**Sponsor:** *Special Team for Amputations, Mobility, Prosthetics/Orthotics*

**Purpose**—Patellofemoral joint disorders such as fixed rotational deformity of the femur can result from congenital, static or traumatic abnormalities of the bones and joints and/or muscle. These disorders create abnormal stress distribution on the articular surface of the patellofemoral joint that may result in osteoarthritis. The specific objectives of this study were to quantitatively access the maximum contact pressure distribution on the articular surface of the patellofemoral joint and the load relaxation behavior of the patella complex under a fixed rotational deformity at various knee flexion angles.

**Progress**—A special apparatus was designed to be used in conjunction with an Instron Material Testing Machine for biomechanical evaluation of the patellofemoral disorders. This system allows one to introduce various degrees of fixed deformities and knee flexion angles to measure the maximum contact pressure distribution on the articular surface using

Fuji pressure-sensitive film. Further, the load relaxation response of the patellofemoral complex can also be measured. Since the soft connective tissues in the patellofemoral complex exhibit time and history dependent behavior, a series of preliminary experiments were performed to determine the required time for complete recovery of the soft tissue in the patellofemoral complex subsequent to each nondestructive test. For data acquisition, the maximum contact pressure distribution on the articular surface of the patellofemoral joint and the load relaxation behavior of the patella complex at fixed rotational deformities ranging from −30 degrees to +30 degrees at 15 degree increments were obtained. The whole procedure was then repeated at knee flexion angles at 0, 30, 60 and 90 degrees. The results from this study will aid surgeons in determining the degree and onset timing of patellofemoral joint disorder resulting from various fixed deformities of the femur.

**Future Plans/Implications**—The next step of this study will be a multidisciplinary animal study to characterize the degenerated articular cartilage resulting from fixed rotational deformities.

# B. Human Locomotion and Gait Training

## WATRACK—A New System for Studying Movement

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

**Purpose**—A new position-measurement system, installed in the Center's Motion Analysis Laboratory, includes two infrared-light-sensitive cameras controlled by an IBM AT PC.

**Progress**—Small, lightweight infrared-light-emitting diodes (LEDs) are attached to a moving element, whose movement is recorded by the cameras. The light projections on the cameras' back-planes are then electronically integrated, and the three-dimensional position of each LED determined. This information is then stored and transferred to the Center's VAX computer for further analysis. The advanced analysis of the LED position information uses a software package named TRACK, which was developed at M.I.T. The package includes a series of subroutines that use the above information to calculate the translational and rotational degrees of freedom of rigid segments, instrumented with the LEDs, and attached, for example, to the lower limbs when the kinematics of gait are being studied.

**Results**—The system has been successfully installed and tested, and its resolution within the system's viewing volume was found to be about one mm for translation and one degree for rotation. The system will be used extensively as researchers at the Center and elsewhere realize its potential. The first clinical study using WATRACK will be of the head movement of a quadriplegic cerebral palsy patient.

## Development of a Posture Sensor and Sensory Biofeedback System for Use in Gait Training of the Locomotion Disabled

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**Sponsor:** *Japanese Ministry of Education*

**Purpose**—In the locomotion-disabled person, such as paraplegic or hemiplegic patients with balance deficits, information about pelvic inclination is most useful from the point of view of rehabilitation. In

the present study, pelvic inclination and its time derivative in the sagittal and frontal plane during walking are measured by the use of an inclinometer based on the gyroscope principle. This posture sensor system is used to evaluate the gait and its improvement, if any, through rehabilitation. It is also expected to use the information so that the patient may grasp its posture by biofeedback through auditory tone.

**Progress**—All the information can be obtained from two kinds of sensors: angular sensors put on the pelvis by belts, and foot-switch sensors on the soles of the patient's shoes. The information is acquired and treated on-line in real-time by a 16-bit microcomputer via A/D converter. Several software programs were developed for measurement and data processing and then tested on the normal subjects' walks and hemiplegic persons' walks.

**Preliminary Results**—It was clarified by preliminary experiments that a graphic presentation shows basic characteristics of each patient's gait. Clinical results are under evaluation. A prototype of a biofeedback system was designed, fabricated, and tested first on normal subjects.

**Future Plans/Implications**—It is expected to quantify the gait of each patient, for use in a rehabilitation program and to evaluate its effects. This posture sensor system will be used in combination with the sensory biofeedback system for rehabilitation in some cases.

## Measurements of Postural Sway

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**Sponsor:** *Liberty Mutual Insurance Company*

**Progress**—The above-mentioned study has generated a large inventory of data describing postural equilibrium in healthy individuals and in patients with neurological disorders. We are presently re-evaluating these data to test a new mathematical model for postural sway. Unlike standard methods of interpreting stabilograms, the form in which our data appears and the results based on our model clearly emphasize differences in postural sway and provide a means of understanding the motor-control scheme that directs the movement.

To further understand the model as a control process, the statistical properties of the stabilogram are being studied. An algorithm to calculate the angular rotations of the center-of-pressure "footprint" has been developed. The algorithm is used to study the statistical properties of the distribution of rotations so that the "random" aspects of the stabilogram can be studied. A stochastic model of the process will then be developed, and the behavior of the model in response to different processes and under different boundary conditions will be studied. Such a model may explain some basic issues in the postural control of the neuromuscular system.

## A Model for Postural Sway

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**Sponsor:** *Liberty Mutual Insurance Company*

**Purpose**—When an individual stands erect, the body makes minor movements over the location of the feet, for the human body is incapable of remaining perfectly still. Standing erect is a complicated task which most individuals accomplish with varying degrees of ease. The purpose of this study is to increase our understanding of the mechanisms that control posture in order to measure and quantify

the amount of dysfunction in individuals with movement disorders.

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

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

The model is being tested by investigating whether a subject exhibits a preference to sway in a particular direction during erect stance. This can be measured by considering the stabilogram as a series of line segments joining the consecutive center of pressure coordinates. A computer program was developed to measure the magnitude and direction of the angles subtended by each contiguous parir of line segments. histogram plots of these "sway angles" are being computed and analyzed for all of our previously collected stabilogram data. A manuscript is under preparation to describe these observations.

## The Clinical Application of Gait Analysis

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**Sponsor:** *Lothian Health Board; Spastics Society; University of Edinburgh; Women's Royal Voluntary Service; Ferranti P.L.C.*

**Purpose**—Our objective was to establish a biomechanical gait analysis facility for the purposes of clinical service, clinical research and teaching.

**Progress**—A gait analysis facility has been established utilizing a Vicon TV-computer motion analysis system (Oxford Metrics), a force measurement platform (Kistler Instruments) and a biological telemetry system (M.I.E. Medical Research Limited).

This facility will be used for a wide range of investigations relevant to the activities of an orthopaedic hospital. A principal activity, initially, is an investigation of the use of biomechanical gait analysis for the assessment of cerebral palsied patients in a routine orthopaedic clinic. This work is being carried out in collaboration with Tayside Rehabilitation Engineering Services, Dundee, Scotland.

## The Effects of Proximal Tibial Osteotomy and Tibial Tubercle Elevation on Knee and Ankle Joint Loading

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**Sponsor:** *The National Health Research and Development Programme, Health and Welfare, Canada; the Physician's Services Incorporated Foundation of Ontario, Canada*

**Purpose**—The aim of this study is to objectively measure changes in gait parameters resulting from valgus high tibial osteotomy for osteoarthritis of the medial compartment of the knee. The effects of the osteotomy and valgus realignment of the ankle and foot will be analyzed and the use of prophylactic foot orthoses in correcting heel and mid-foot alignments will be explored.

The specific goals of this project include: 1) using the results of gait assessment, we hope to predict

the optimal size of tibial wedge and hence the angle of knee alignment that will best reduce pain and improve functional gait; and 2) investigating the minimization of secondary stresses at the ankle through the use of simple shoe wedges and orthoses.

**Progress**—Patients undergo gait assessments prior to surgery and at 3, 6, and 12 months postoperatively. Each gait assessment consists of 3 runs of standing on one leg and 5 runs of walking data for each side. Simultaneous recordings of electromyography, force plate, footswitch and kinematic data are taken for each run. Electromyography is recorded from the vastus medialis, rectus femoris, tibialis anterior, gastrocnemius, medial and lateral hamstrings bilaterally. Areas of contact under the feet are recorded from a glass-top platform which has light sources on either side.

Functional and clinical assessments include passive and active knee range of motion, knee strength, and a questionnaire dealing with pain and activities of daily living. Comprehensive models of the knee and ankle have been developed which incorporate the internal forces due to muscle and ligament structures as well as the external moments of force about the joint. From this model, individual muscle forces, ligament forces, the overall joint load and the location of the joint load in the knee compartments, can be calculated.

**Preliminary Results**—Thirty patients have been assessed preoperatively, and of these, eleven patients have completed the protocol. Four patients have completed their 6-month assessment, two patients have completed their 3-month assessment, and seven patients have withdrawn from the study. All normal subjects have completed gait assessments. A total of 59 gait studies were completed in 1986.

Preliminary results of eight subjects were presented at the North American Congress on Biomechanics (NACOB) in August in Montreal, Quebec. Results include a decrease in mean maximum knee joint load per kg body weight from 2.485 ± 0.774 N/kg preoperatively to 1.740 ± 0.297 N/kg post operatively. This maximum occurred at an average of 17.4 ± 7.4 percent of the gait cycle preoperatively, and at an average of 29.3 ± 12.7 percent of the gait cycle postoperatively. These results may be compared with average normal values of 2.500 ± 0.500 N/kg maximum knee joint load per kg body weight occurring at 21.5 ± 8.2 percent of the gait cycle. An average preoperative value of 8.00 ± 3.30 degrees of varus compared with an average postoperative value of 9.25 ± 4.55 degrees of valgus at the knee leads to a shift of percent joint load on the medial side of the knee from an average of 85.69 ± 8.42 percent preoperatively to an average postoperative value of 68.94 ± 16.68 percent. Mean values for normal subjects were determined to be 3.2 ± 2.7 degrees of varus at the knee, and 92.0 ± 10.0 percent joint load on the medial side of the knee.

Other results include an increase in the mean speed of walking, from 0.800 ± 0.208 m/s preoperatively to a mean post-operative speed of 0.896 ± 0.174 m/s, and a significant decrease in subjective perception of pain from the preoperative to the postoperative period.

**Publications Resulting from This Research**

**Effects of Proximal Tibial Osteotomy on Knee Joint Loading.** Cairns B, Naumann S, Tepperman P, Kekosz V, *Proceedings of the North American Conference on Biomechanics* 11:283-284, Montreal, Quebec, Canada, 1986.

## Quantitative Measures for Assessing Therapeutic Effectiveness

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**Sponsor:** *National Institute on Disability and Rehabilitation Research*

**Purpose**—These studies will develop and test measures capable of evaluating the effects of intervention strategies in the management of arthritis; develop a reference database for the parameters of gait, range-of-motion, and anthropometric data for use in pattern recognition studies; and begin preliminary assessment of subjects displaying pathology or symptoms associated with gait.

**Progress**—Our approach has been directed towards the development of a gait vector which exhibits both direction and magnitude and defines a point in a

multi-dimensional space. Each point represents the measured parameters at a particular time along the gait cycle; thus, a series of vector-defined points will form a time-dependent curve. Given a sampling of normal curves from subjects who are close in age and size to the subjects being tested, a mean normal curve can be determined. A bounding envelope around the mean normal curve is defined to contain normal gait function based on a reasonable statistical level of confidence. This boundary defines a discriminant function for the recognition of pathological patterns and a baseline for comparing the effects of different treatment modalities. Gait vectors for individual subjects are calculated from the patient database, which includes data from patients with osteo, rheumatoid, and other types of arthritis.

If a subject's gait deviates outside the normal boundary region at any point in time, then the distance between the point and the boundary is computed as a function of time. The vector direction indicates which parameters are contributing to the abnormal gait function. The vector magnitude indicates the degree of abnormality of these parameters. As the subject's gait curve is compared to the normal boundary, each deviation is added to a running sum to give a measure indicative of total deviation from normal. The time history of the actual deviation from the mean curve is also considered. The summation gives a quantitative measure from normal, while the time history of deviation indicates the source of the deviation and identifies the portion of the cycle where significant deviations have occurred.

**Preliminary Results**—Interpreting large amounts of data in traditional formats has not been very successful. In order to overcome this difficulty, we have developed techniques for animating a human figure on a computer screen in which the limbs are driven by the data collected in the lab on our population of subjects.

In addition, three-dimensional graphs showing scatter-plots of the data have been developed. These graphs enable the clinician to analyze and interpret patterns in data that may not be discernible from two-dimensional graphs. The walking figure and the associated data can be viewed from any direction. Zooming facilitates close-up views of specific gait anomalies.

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

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**Sponsor:** *National Institute on Disability and Rehabilitation Research*

**Purpose**—This work stems from an initial effort to improve gait training for above-knee amputees, and is now branching into application for others with similar gait pathologies. Earlier work resulted in development of a self-contained biofeedback system that is worn by the amputee during gait training sessions. Hip angle is measured by a radio goniometer and axial load is determined by strain gauges in the shank of the prosthesis. In this system, called the MIT Strider, these parameters are recorded in a waist pack, which also provides feedback to the patient as a tone that varies with the measured load or angle. The Strider has been used successfully in a clinical setting.

Modifications to this system, including a wireless data-link that telemeters the data from the patient to a remote personal computer, yielded the MIT Trainer. With the computer, data can not only be stored and replayed later, but generalized graphics software has been written allowing visual biofeedback in the form of stick figure images on the CRT, which move as a representation of the measured angle and load. The auditory feedback can be a tone that sounds when a preset threshold angle is attained.

**Progress**—The Trainer system has been applied in gait training sessions with amputees, as well as in measurement of hip angle during squat weightlifting exercises, and in feedback of knee angle during leg extension exercises for an athlete undergoing knee rehabilitation. It has also been recognized that many hemispherically affected stroke patients exhibit gait

pathologies similar to those of A/K amputees, including loss of control at the ankle and knee and lessened extension at the hip during stance. Thus, the hip angle measurement facet of the system has been used in gait therapy sessions with two stroke patients.

The first of these patients was extremely attentive to the system feedback, consciously working to attain the threshold angle, and therapists were very happy with the system's application. The second patient illustrated one hardware shortcoming, as she had such minimal control at the hip that the leg sometimes rotated externally during swing. This gross out-of-plane motion of the radio goniometer caused some unreliable output, indicating that the method of joint angle measurement utilized in the system may merit further investigation. Overall, patient and therapist response was quite positive, and the system is undergoing continued testing with stroke patients. Plans are also underway to utilize the device with other patients suffering motor coordination deficits, such as those with cerebral palsy or head and spinal cord injuries.

**Publications Resulting from This Research**

**Human Movement Biofeedback Training and Diagnostic System.** Belot JR, Flowers WC, *ACEMB*, Baltimore, MD, September 13-16, 1986.

**A Radio Goniometer for Use in Training Above/Knee Amputees.** Cullen CP, Flowers WC, *Proceedings of the 2nd International Conference on Rehabilitation Engineering*, 268-269, Ottawa, Canada, 1984.

**A Preliminary Report on the Use of a Practical Biofeedback Device for Gait Training of Above/Knee Amputees.** Flowers WC, Cullen CP, Tyra KP, *Journal of Rehabilitation Research and Development*, 23(4):7-18, October, 1986.

**Computer Control of A/K Prostheses Using Sound Leg Landmarks.** Linske KA, Flowers WC, *ACEMB*, Chicago, IL, September 30-October 2, 1985.

**A System for Measuring the 3-Dimensional Gait of an Above/Knee Amputee Wearing a Prosthesis Simulator.** Stein JL, Flowers WC, *Proceedings of the 2nd International Conference on Rehabilitation Engineering*, 233-234, Ottawa, Canada, 1984.

## Feasibility Study: Evaluation of Total Knee Replacement by Gait Analysis

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**Sponsor:** *National Institutes of Health*

**Purpose**—This grant is requested to develop three areas of special interest. The first is applied research in which we aim to: 1) develop a necessary and sufficient database for the rational planning of health services to arthritics, and 2) develop and evaluate model components of cost-effective health care delivery for arthritis patients. Thus, under Community Component, we propose to develop and critically evaluate: a 7-day rehabilitation work schedule; a model health care system for arthritis disability; stepped-up rehabilitation services to homebound patients; a system of follow-up of rheumatic disease patients discharged from a tertiary care facility; a patient-oriented strategy to improve clinical outcomes; and an educational strategy for the primary prevention of low back injuries in the work place. As one of the 4 major joint replacement centers in the world, we propose to evaluate the cost-effectiveness of joint replacement by a multidimensional outcome assessment. We seek to document the economic burden to arthritics and shortfalls in the present health care reimbursement scheme. We propose to evaluate the means by which interventions can be evaluated, and compare the relative merits of existing health status functional instruments.

The second priority is the development of a Core Unit for quantitative research methods, Clinical Epidemiology and Evaluation Research, which would overlap with many activities of the Center and would aid investigators in training and establishing investigators. The Unit would support at least 10 projects, from the day-to-day management of special disease registries, to clinical studies directed at improving clinical strategies and decision making in rheumatology, and applications of basic research.

## A Clinical Gait Recording System

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**Sponsor:** *The Northern Ireland Prosthetic Orthotic and Aids Service*

**Purpose**—This continuing project is concerned with the production of a portable microcomputer-based gait recording system which is suitable for clinical use.

**Progress**—The Foot Pressure Profile Platform (FPPP) continues in production as the "Musgrave Footprint." The instrument records and presents pressure distribution under the sole of the foot, either during standing or walking.

**Results**—Information relating to center of pressure, maximum pressure and pressure/time characteristics may be examined on screen or on print-outs. Either one or two pressure plates may be used, interfaced to either a BBC or an IBM microcomputer. Software options continue to be augmented as is the resolution of the pressure platform.

## Gait Abnormalities in Hemiplegia: Their Correction by Ankle-Foot Orthoses

**Justus F. Lehmann, M.D.; Sandra M. Condon, M.S.; RPT; Robert Price, MME; Barbara J. de Lateur, M.D.**
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**Sponsor:** *None Listed*

**Purpose**—Hemiparetic gait is characterized by slow speed and poorly coordinated movements. Because the values of gait parameters vary with changes in speed, the slow speed that is typical of hemiparetic gait necessitates applying controls for the influence of speed when comparing hemiparetic and able-bodied persons.

**Progress**—Gait kinetics and kinematics were measured in seven hemiparetic and seven able-bodied adults to compare their gait patterns at similar speeds and to assess the effectiveness of ankle-foot orthoses which were double-stopped in 5 degrees of dorsiflexion or 5 degrees of plantarflexion.

**Results**—Hemiparetic persons ambulating without the orthoses had a shorter step length, longer duration stance, and shorter duration swing than normal. They displayed greater than normal flexion of the affected hip during midstance, which, by putting the center of mass farther in front of the knee, may explain the increased knee extension moment due to vertical force. Affected hip adduction during single support was less in hemiparetic persons than in able-bodied persons, indicating a decreased lateral shift to the paretic side. During the swing phase, the affected limbs of hemiparetic persons were in less knee flexion and less dorsiflexion than normal, necessitating circumduction to achieve toe clearance. Ankle-foot orthoses increased walking speed to normalize heelstrike duration through use of an optimally adjusted plantarflexion stop. An improperly adjusted orthosis may produce an exaggerated knee flexion moment resulting in knee instability.

### Publication Resulting from This Research

**Gait Abnormalities in Hemiplegia: Their Correction by Ankle-Foot Orthoses.** Lehmann FJ, Condon SM, Price R, de Lateur BJ, *Archives of Physical Medicine and Rehabilitation*, 68, 1987.

# C. Other

## Optimal Biomechanical Design/Development of Arm-Powered Mobility Devices

**Michael Zomlefer, Ph.D.; Douglas Schwandt, M.S.; Jeffrey Aldrich, Ind.Des.; Tim Hight, Ph.D.; Doug Martin, Ph.D. Candidate; Russ Miller, B.S. Candidate; Jason Lee, M.S.; Linda Hollis, B.S.**
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**Sponsor:** *VA Rehabilitation Research and Development Service*

**Purpose**—The development of upper limb simulation and modeling tools is important to future design efforts attempting to optimize arm-powered drive systems and create better mobility and exercise devices for individuals with lower limb disability. Modern control theory, when coupled with human biomechanical performance measurements, can lead to nearly optimal arm-powered drive systems. This involves the development of a tractable, computerized, biomechanical model for the upper limb as it applies to a broad spectrum of arm-propulsion tasks. Given specified performance criteria (such as maximum power output or maximum efficiency), this model may then be used to quickly create optimal configuration and dimensions for any proposed drive system and purpose.

**Progress**—Experimental results obtained from subjects operating a variety of arm-powered ergometer drive systems will be used to help define and refine the biomechanical model of the upper limb performing optimizable ergonometric tasks, applying modern optimal control theory. In order to develop a more universal mathematical model, several drive and load systems will be employed, each with such variable features as crank length for arm cranking experiments, or lever length and pivot position for oscillating lever propulsion. Kinematic and dynamic data will be acquired, and analyzed with simultaneously collected electromyograms (EMGs).

The rotary crank and reciprocating lever laboratory arm-powered ergometer systems have been designed and fabricated. Design work was carried out using the computer-aided design facilities at the Stanford Center for Design Research. Mathematical equations of motion describing the dynamics of the arm-cranking task have been developed for entry into the computer. Dynamic and EMG data acquisition systems are being assembled in preparation for the initial round of experimentation and analysis. Experiments will be carried out in conjunction with Santa Clara University Biomechanics Laboratory.

**Results**—Initial experimental test runs are underway on the ergometer. This will be followed by variable arm-crank length and shoulder to crank center experiments on able-bodied and paraplegic subjects. Data will be analyzed and results reported.

**Future Plans/Implications**—It is anticipated that a 3-dimensional extension of the computer model will be the subject of work building upon this study. In addition, the combined theoretical/experimental approach of this study can easily be extended to other functional tasks such as reaching, grasping, moving, and manipulating objects. Better models for limb dynamics will also serve functional electrical exercise and biofeedback strategy research, through improved understanding of muscle activation sequence.

### Publications Resulting from This Research

**A Modular Multiple Drive/Load Ergometer for the Development of an Optimal Biomechanical Model of the Upper Limb.** Schwandt DF, Aldrich JC, Zomlefer MR, *RESNA 9th Annual Conference*, 6:429-431, Minneapolis, MN, June 1986.

## Biofeedback System for Postoperative Hand Rehabilitation

**Donald Neth, M.S.; Kevin Waters; Steven I. Reger, Ph.D.**
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**Sponsor:** *The Cleveland Clinic Research Foundation*

**Purpose**—A biofeedback device has been developed for use in postoperative rehabilitation of the hand. A varied program of exercises can be prescribed and monitored by adjusting the different settings on the device. The patient is asked to squeeze a rubber bulb that is attached to the biofeedback unit. The force of the squeeze, as well as the duration and frequency of squeezing, are monitored. If the patient fails to squeeze the bulb the prescribed number of times and with the prescribed force, a warning light will be activated. If the patient still fails to squeeze the bulb in the prescribed manner, a buzzer will sound. As a reward for correct completion of a prescribed task, a television or record player will remain operating for the user's viewing enjoyment. When used with children (or some adults), this reward can serve as an effective reminder; incomplete and incorrect performance of the hand exercise task will result in the deactivation of the television set.

**Progress**—A simplified prototype of the device has been built and successfully tested in the Cleveland Clinic Department of Occupational Therapy. A second prototype with full capabilities is currently being assembled.

## Dynamic Positional and Electromyographic Monitoring of Sitting Posture

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**Sponsor:** *Hospital for Sick Children Foundation; The National Health Research and Development Programme, Health and Welfare, Canada*

**Purpose**—This study was designed to objectively quantify the activity of selected muscles while in the sitting position. Both normal children and children with cerebral palsy (CP) are being studied while changes of seat inclinations are made. The specific goals of the project include: 1) detection of muscle imbalance (asymmetry) during sitting; 2) investigation of the effects of techniques aimed at improving spinal alignment; and 3) data collection concerning sitting posture of children with CP which will assist in the design of new sitting systems.

**Progress**—This study involves 20 children: 10 normal and 10 with cerebral palsy (mildly involved spastic diplegia) ranging in ages from 5 to 12 years old. The protocol consists of four sessions, each divided into two ten-minute phases. A 20-minute period begins to approach the functional sitting time for these children during typical classroom activity.

The protocol will enable us to compare the postural parameters between normal (or 0 degree) sitting, and sitting on either a 10 degree or 15 degree forward tilting seat base; and between relaxed sitting at a forward 15 degree tilt and maximum voluntary extension of the back. Monitoring 0 degree sitting angle in the second phase facilitates the observation of any possible fatigue factors.

**Preliminary Results**—To date, 15 children, 8 with cerebral palsy and 7 normals, have completed the protocol. It appears that the optimal angle for the seat base inclinations is closer to 10 degrees than 15 degrees, because although the postural parameters of trunk stability and spinal elongation are similar at both 10 degrees and 15 degrees, muscle activity is greater at 15 degrees than 10 degrees.

The improvements in sitting posture observed in children with cerebral palsy, obtained by tilting the seat base forward, are of greater therapeutic value despite the increased back extensor muscle activity. Tipping the seat base forward causes an increase in mid-thoracic and lumbar EMG, although bilaterally, the muscle activity became more symmetrical. Generally, hamstring activity was reduced.

The changes in muscle activity were much more pronounced in children with cerebral palsy than with normal children. An anteriorly tipped-seat appears to facilitate spinal elongation and increase trunk stability (reduce radius of movement) in the cerebral palsy child.

**Future Plans/Implications**—The present monitoring system and protocol appears to be an objective method of evaluating posture in children with cerebral palsy. That is, trunk stability, spinal elongation, and back extensor muscle electromyographs can be monitored accurately and objectively. The work in this area will continue.

**Publications Resulting from This Research**

**Positional and Electromyographic Investigation of Sitting Posture in Children with Cerebral Palsy,** Bablich K, Sochaniwsky A, Koheil R, *Developmental Medicine and Child Neurology* 28(S53):25, 1986.

## Mechanics of Rising From the Seated Position

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**Sponsor:** *The Northern Ireland Prosthetic Orthotic and Aids Service*

**Purpose**—The aim is to develop and evaluate a system whereby a disability can be defined and its progress, either degenerative or corrective, can be monitored by analyzing the subject's mode of rising from a seat.

**Progress**—A low cost force plate has been designed and constructed to measure the reaction force, during standing, under the feet. A similar instrument is being constructed for the seat of a variable geometry chair, for which armrests are also being developed with instrumentation to measure forces. Electrogoniometers are being used to record joint angles of the leg and their interfacing with a microcomputer is well advanced. It is anticipated that preliminary results will be recorded during the latter months of 1987.

## A New Approach in Muscle Training to Rehabilitate the Hand in Leprosy

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**Sponsor:** *Poona District Leprosy Committee*

**Purpose**—In leprosy a hand, with its atrophic musculature, poses a formidable challenge as far as anesthesia during tendon transfer surgery and rehabilitation after surgery is concerned. An ideal rehabilitative exercise in such circumstances should be inexpensive, easy to perform repeatedly, and should produce a normal hand function as soon as possible. A sheet of newspaper, when crumpled by hand into a ball, constitutes an ideal exercise for rehabilitation of the hand following surgery. The exercise increases the speed of finger movement, as well as static and dynamic strength and coordination between fingers in space (due to infinite positional combinations). There is rapid increase in the flexibility of fingers with high integration of extrinsic as well as intrinsic muscles of the hand. With this exercise we have been able to improve the function of the hand remarkably well and the rehabilitation time following surgery is drastically reduced, with function returning close to normal. The patient holds one corner of the paper between his thumb and index finger and starts gathering it into his hand without the aid of his other hand or any other structure in the vicinity. He is advised to make use of all fingers consciously. Once he is able to gather the paper in his hand; he compresses it into a small firm ball which can be compressed no more.

**Progress**—Fifty patients ranging from 20 to 55 years of age and who had undergone tendon transfer surgery for opponens and lumbrical replacement

using sublimis as a motor participated in the study. The following schedule was observed in these cases: a) three weeks in plaster cast following surgery; b) achievement of voluntary lumbrical position without splints within 1 week; c) start with paper crumpling by the end of first or beginning of second week; d) complete fist by the end of third week; and, e) total rehabilitation time five to eight weeks following surgery.

**Results**—It was noticed that the achievement of a fist was very rapid (average time being 2 to 3 weeks, particularly observed in the donor finger). With this exercise both initiation and completion of profundus action at the distal interphalangeal joint of the donor finger was quite early as compared to the previous conventional physical therapy methods. Profundus also worked freely at the proximal interphalangeal joint and took over the sublimis function quite well. There was an enhanced effect on the gliding of profundus in the donor finger. Re-education of profundus to function without sublimis in the donor finger was achieved very quickly and efficiently.

The average time for the completion of fist through paper crumpling was 12.4 days in 36 patients and 33.5 days in the other 14 patients. The average time for the completion of fist after removal of the plaster cast was 26.8 days in 30 patients and 57 days in the other 20 patients. Patients who required more than two weeks to achieve the fist had one of the following problems post-operatively: delay in achievement of voluntary lumbrical position; stitch abscess; or severe adhesions round the profundus tendon of the donor finger.

Paper crumpling constitutes an ideal exercise for rehabilitation of patients following hand surgery, especially in leprosy. The exercise is easy to understand, inexpensive, and can be done any time, anywhere, and as many times as possible. It gives excellent visual feedback and does not injure the insensitive hands. The exercise adjusts itself to the needs of the patient remarkably well and allows for a gradual rate of increase in the performance of the task.

## Comparison of Floor Sitting and Wedge Kneeler: Their Effect on Posture and Upper Extremity Range of Motion in Children with Cerebral Palsy

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**Sponsor:** *Special Children's Center, Inc., Ithaca, NY*

**Purpose**—The objectives of this project were to apply the flexible ruler technique for measuring lumbar curve changes to a pediatric population; to develop measures of active, functional upper extremity range of motion; and to document the changes in posture and functional range for children with cerebral palsy in various sitting positions/equipment using these measures. Children with cerebral palsy frequently exhibit an uncorrected sitting posture composed of posterior pelvic tilt, flattened lumbar curve, and thoracic flexion. These are associated with shoulder internal rotation and upper extremity postures which are considered to limit upper extremity range of motion. Several types of adaptive seats have been proposed to correct posture. Corrected hip and trunk posture is hypothesized to correct upper extremity posture and therefore to affect active, functional range of motion. However, clinically useful and accurate measures of posture and active, functional range of motion have not been implemented or tested with a pediatric population.

**Progress**—A pilot study has been completed using a 4-and-a-half-year-old child with spastic quadriplegic cerebral palsy. Lumbar curve measurements have been recorded using the flexible curve when seated initially and after upper extremity range measurements have been taken. The conditions measured were: floor-sitting independently, bench-sitting on a level bench, and bench-sitting on a wedge bench with a 45-degree forward tilt. The wedge bench was developed at the Special Children's Center to replace floor sitting for children with spastic type cerebral palsy. The design is similar to a back chair which combines both sitting and kneeling. Upper extremity range is recorded on graph paper attached to an upright easel. The graph

is level. The horizontal axis is placed at shoulder level. The vertical axis is placed at midline. The point touched with the right and the left index finger is marked on the graph paper at 0, 30, 90, 120, 150, and 180 degrees. The distance from the child's anterior, superior, and iliac spine to the easel is the same in each condition. The child's seat is wooden and a seat belt is used to prevent the child from leaving the seated position.

**Preliminary Results**—The flexible curve has allowed static lumbar positions to be recorded. Measurements of the lumbar curve have changed in the expected direction. The curves are apparently posterior in floor-sitting, flattened in level bench-sitting, and anterior in wedge bench-sitting. The upper extremity range measurements also show the expected change on gross inspection of the graphs. Range increases from floor-sitting to level bench-sitting to wedge bench-sitting. Statistical analysis remains to be completed. However, it has been difficult to relate the lumbar curve measurements to the range measurements because of the dynamic spinal movement during active range of motion in the upper extremity. Each measure taken separately does appear to support the use of special seating to correct posture and to improve functional range.

**Future Plans/Implications**—We plan to continue this study by adding subjects and attempting to develop a dynamic measurement of lumbar curve in pediatric patients. Suggestions from the field on this topic would be most welcome.

## Design of Instrumentation to Quantify Upper Extremity Motor Control of Children with Cerebral Palsy: Pilot Study

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**Sponsor:** *United Cerebral Palsy Research Educational Foundation*

**Purpose**—The aim of this project was to develop instrumentation to quantify motor performance of the upper extremity and monitor muscular responses contributing to trunk stability during a reaching task. Emphasis was placed upon developing a standardized experimental task and instrumentation to collect temporal and muscular measures using an automatic data acquisition system.

**Progress**—Speed and time measures have been used extensively in motor control research to quantify performance. A choice response time task for three positions was designed to quantify upper extremity motor function. Instrumentation consisted of a series of pressure sensitive switches (6.5 cm x 6.5 cm) mounted in a row on an adjustable table. This table is placed directly in front of the subject, matching the center switch with the midline of the body. Distance between the switches is easily adjustable to accommodate individual abilities of each subject. EMG activity was monitored from three muscle sites: anterior deltoid, and bilaterally from the lumbar erector spinae (L3 segmental level).

Software developed to run the experimental protocol contained subroutines to: 1) input demographic data; 2) sample, average and compute the EMG threshold level; 3) randomly present a stimulus or cue; 4) strobe the computer to sample EMG data; and, 5) store and calculate temporal response data.

**Results**—Four children with cerebral palsy (spastic diplegia) aged five to eight years old participated in the study. It was observed that non-dominant lower back erectors showed activation prior to the deltoid muscle and the dominant side of low back extensor. This observation provided valuable insight into the coordination of the muscular actions contributing to trunk stability during the performance of a reaching task.

**Future Plans/Implications**—Further development shall be directed towards refining software and data acquisition with the use of one computer only, and evaluating the effects of selected seat inclinations on upper extremity motor control.

### Publications Resulting from This Research

**Design of Instrumentation to Quantify Upper Extremity Motor Control of Children with Cerebral Palsy.** McClenaghan BA, Bablich K, Sochaniwsky A, Koheil R, *Proceedings of the Ninth Annual Conference on Rehabilitation Technology*, Minneapolis, MN, 6:158-160, June 1986.