Journal of Rehabilitation Research and Development

Rehabilitation R & D Progress Reports 1990

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II. Biomechanics

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A. Bone and Joint Studies

[57] Biomechanics of Patellofemoral Joint Disorders: In Vitro Human Cadaver Study

Sanford H. Anzel, MD; Thay Q. Lee, MS
VA Medical Center, STAMP Program, Long Beach, CA 90822

Sponsor: *VA Rehabilitation Research and Development Service (Project #A474-RA)*

Purpose—The patellofemoral force system is complex and considered to have a strong correlation with patellar disorders such as chondromalacia and subsequent arthrosis. The biomechanics of patellofemoral joint disorders that result from the problems associated with soft tissue or the tibia have been well-documented. However, the biomechanics of the patellofemoral disorders resulting from angular and torsional deformities of the femur have not been determined. The objective of this study was to determine the quantitative effects of fixed rotational deformities of the femur on patellofemoral contact pressures and the tension in quadriceps tendon in human cadaver knees.

Methodology—Seven fresh frozen cadaver knees were used. The specimens had no previous surgery, with macroscopically intact cartilage, radiographically normal bone structure, and intact joint capsule. The ages were unknown, but they appear to have been between 60 and 80 years old. The specimens were carefully dissected leaving only the femur, tibia, joint capsule, and quadriceps tendon. The femur and the tibia were then cut 25 cm away from the tibial plateau, and the fibula was eliminated. The specimen was clamped rigidly into steel cylinders and mounted onto a custom jig specifically built to be used in conjunction with an Instron machine. This system simulates fixed rotational deformities of the femur at various knee flexion angles and permits simultaneous measurement of the patellofemoral contact pressures and the tension in the quadriceps tendon.

Once the specimen was securely mounted and positioned at a desired knee flexion, the neutral position of the patellofemoral joint was determined; then the patellofemoral contact pressures were measured under 200 N of tension in the quadriceps tendon using Fuji pressure-sensitive film (range: 0.2 to 2.0 MPa). For the patellofemoral contact pressures in rotated state, a new film was inserted and the tension in the quadriceps tendon was maintained at 200 N for 45 minutes in neutral position before rotating the specimen. The internal and external rotation of 20 and 30 degrees was accomplished at 2 rpm using a motorized assembly built into the jig while continuously monitoring the tension in the quadriceps tendon. The entire procedure was performed at knee flexion angles of 30, 60, 90, and 120 degrees. The contact pressures from Fuji film were quantified by using a calibrated scale from the manufacturer which was also verified in the laboratory by compressing cylindrical rubber discs with an Instron machine.

Results—The *in vitro* study revealed that the increase in the degree of fixed rotation of the distal femur in human cadaver knees resulted in a nonlinear increase in patellofemoral contact pressures on the contralateral facets of the patella (i.e., external rotation resulted in a contact pressure increase on the medial facet and internal rotation resulted in a contact pressure increase on the lateral facet of the patella). With the initial isometric tension of 200 N in the quadriceps tendon for 30, 60, 90, and 120 degrees of knee flexion, the peak contact pressure showed no significant differences between the medial and lateral facets of the patella in neutral position ($p > 0.5$). Upon 20 degrees of femur rotation, only a slight increase was noted for the tension in the quadriceps tendon and the contact pressures in the contralateral facets of the patella. However, upon 30 degrees rotation, both the external and internal rotations of the distal femur resulted in significant increase in the tension of the quadriceps tendon and the contact pressures on contralateral facets of the patella. In addition, the external rotation for knee flexion angles of 30, 60, and 90 degrees showed significantly higher peak contact pressure increases on the medial facet of the patella as compared to the internal rotation of the femur ($p<0.05$). This study provides baseline information regarding changes in patellofemoral contact pressures that may be significant for the development of chondromalacia patella and subsequent arthrosis due to fixed rotational deformities of the femur. Further, surgical procedures involving osteotomies of the distal femur should only be performed after an accurate assessment of the femur rotation and angulation.

[57a] Biomechanics of Patellofemoral Joint Disorders: In Vivo Canine Study

Purpose—The objective of this part of the study was to determine the long-term response of the articular cartilage on the retropatellar surface to 30 degrees of fixed rotational deformities (internal and external) of the femur in a canine model.

Methodology—Fifteen skeletally mature mongrel dogs were used. Thirty degrees of fixed rotational deformities of the femur were surgically imposed using six-hole Dynamic Compression Plates on 12 experimental animals. Three remaining animals were used as controls. Twelve experimental animals were divided into four groups with three dogs in each group: bilateral internal rotations (3 and 6 months), and bilateral external rotations (3 and 6 months). All the procedures were performed bilaterally to insure even weightbearing. At the end of the experimental period, the dogs were euthanized and the hind legs were disarticulated at the hip and the ankle joint. Then all the musculature, ligaments, and menisci were carefully dissected away to expose the articular surface of the patellofemoral joint for indentation test. The unrelaxed (0.1 sec) and relaxed (2000 sec) shear modulus were determined for each quadrant of the retropatellar articular cartilage using a custom-built indenting apparatus (force of indentation = 0.98 N, diameter of the cylindrical ram indenter = 1.0 mm). The mathematical analysis was based on theoretical indentation mechanics of an infinite elastic layer bonded to a rigid half-space. The elastic layer corresponds to the articular cartilage, and the rigid half-space to the underlying bone. For this model, the analysis by Hayes provides an exact elastic solution for indentation by a plane-end cylindrical ram, assuming the shear traction between ram and the layer is negligible for small strains.

Results/Implications—For the *in vivo* canine study, the morphological examination revealed early signs of arthrosis (redness of the articular cartilage) on the retropatellar surfaces at 6 months for both the internal and external femur rotations. The indentation tests showed no difference between each quadrant of the patella for all experimental groups regardless of the direction of the femur rotation ($p>0.5$). However, a statistically significant decrease was observed for both the unrelaxed and relaxed shear modulus at 6 months for both directions of the femur rotation ($p<0.05$). This was further supported by histological findings where the disorganization of the collagen fibers and blistering in the tangential layer were observed. These findings indicate that the cartilage softening occurred on patellar facets with both the increased and decreased contact pressures.

This study provides baseline information regarding changes in patellofemoral contact pressures that may be significant for the development of chondromalacia patella and subsequent arthrosis due to fixed rotational deformities of the femur. Further, surgical procedures involving osteotomies of the distal femur should only be performed after an accurate assessment of the femur rotation and angulation.

Recent Publications Resulting from This Research

Influence of Fixed Rotational Deformities of the Femur of Patellofemoral Contact Pressures. Lee TQ, Bennett KA, Anzel SH, First World Congress of Biomechanics, I:61, 1990.

Influence of Fixed Rotational Deformities of the Femur of Patellofemoral Contact Pressures–Human Cadaver Study. Lee TQ, Anzel SH, in Proceedings of the Western Orthopaedic Association, LA Chapter, 1990.

The Influence of Fixed Rotational Deformities of the Femur on the Patellofemoral Joint: In Vitro and In Vivo Assessment. Lee TQ, in Proceedings of the 14th Annual Meeting of the American Society of Biomechanics, 1990.

The Influence of Fixed Rotational Deformities of the Femur on the Patellofemoral Joint: In Vitro and In Vivo Assessement (Abstract). Lee TQ, J Biomech, 1990.

Three and Six Months Assessment of the Articular Cartilage Resulting on the Retropatellar Surface Resulting From Fixed

Femur Rotation: In Vivo Canine Study. Lee TQ, Bennett KA, Anzel SH, in Proceedings of the First World Congress of Biomechanics, I:60, 1990.
The Influence of Fixed Rotational Deformities of the Femur on the Patellofemoral Contact Pressures in Human Cadaver Knees. Lee TQ et al., Clin Orthop Rel Res (in press).

[58] Surgery Simulation Computer Models to Study Reconstructive Surgeries

Melissa G. Hoy, PhD; Joseph M. Rosen, MD; Felix E. Zajac, PhD; Scott L. Delp, PhD; J. Peter Loan, MS
Rehabilitation Research and Development Center, VA Medical Center, Palo Alto, CA 94304-1200

Sponsor: *VA Rehabilitation Research and Development Service (Project #B554-RA)*

Purpose—Function can sometimes be restored to patients with movement disabilities via surgical reconstruction of musculoskeletal structures. Surgical reconstructions, however, often compromise the capacity of muscles to generate force and moment about the joints. Patients that cannot generate sufficient muscle force or joint moment are left with weak or dysfunctional limbs. The goal of this project is to understand the connection between the parameters of various surgical procedures and the force and moment-generating capacity of the muscles.

Methodology—We have developed a graphics-based model of the human lower extremity to simulate the effects of musculoskeletal reconstructions on muscle function. The lines of action of 43 muscle-tendon complexes were defined based on their relationships to three-dimensional bone surface models. A model for each muscle-tendon complex was formulated to compute its force-length relation. The kinematics of the lower extremity were defined by modeling the hip, knee, ankle, subtalar, and metatarsophalangeal joints. Thus, the maximum isometric force and joint moment that each muscle-tendon complex develops can be computed at any body position. Since the model is implemented on a computer graphics workstation, we can easily manipulate the model parameters according to various surgical techniques. For example, the origin-to-insertion path of a muscle-tendon complex can be graphically altered to simulate a tendon transfer. The results of the simulated surgeries can be displayed in terms of presurgery and postsurgery muscle forces, joint moments, and other biomechanical variables.

Results—We have applied our model of the lower limb to study tendon surgeries and pelvic osteotomies. Our analysis of tendon lengthenings indicates that the forces generated by the ankle plantarflexors are extremely sensitive to surgical lengthening of tendon; other muscles are much less sensitive. Quantifying the sensitivity of the muscle forces and joint moments to changes in tendon length provides important new data needed to design effective tendon surgeries. Our simulations of the Chiari pelvic osteotomy suggest that osteotomies performed with high angulation shorten the hip abductors and may lead to the commonly observed weakness of the hip abductors. Our results show that horizontal osteotomies preserve the moment-generating capacity of the hip abductors and may therefore decrease the number of patients that limp after surgery.

Just as computer graphics systems have enhanced other areas of design and analysis, we have found that an interactive, graphics-based model of the human lower extremity is an effective new tool for designing and analyzing surgical procedures.

Recent Publications Resulting from This Research

A Computer Graphics System to Study Human Movement. Delp SL et al., in Proceedings of the Twelfth International Congress of Biomechanics, 169-170, 1989.
An Interactive Graphics-Based Model of the Lower Extremity to Simulate Tendon Transfer Surgeries. Delp SL et al., Adv Bioeng 167-168, 1989.
Biomechanical Analysis of the Chiari Pelvic Osteotomy: Preserving Hip Abductor Strength. Delp SL et al., Clin Orthop 254:189-198, 1990.
Computer Simulation of Lower Extremity Tendon Transfers. Delp SL et al., in Proceedings of the 36th Annual Meeting of the Orthopaedic Research Society, 537, 1990.
An Interactive Graphics-Based Model of the Lower Extremity to Study Orthopaedic Surgical Procedures. Delp SL et al., IEEE Trans Biomed Eng 37(8):757-767, 1990.
A Musculoskeletal Model of the Human Lower Extremity: The Effect of Muscle, Tendon, and Moment Arm on the Moment-Angle Relationship of Musculotendon Actuators at the Hip, Knee, and Ankle. Hoy MG, Zajac FE, Gordon ME, J Biomech 23:157-169, 1990.
Understanding Human Movement with Computer Graphics. Delp DB, Delp SL, Soma: Eng Hum Body 3:17-25, 1990.

[59] Patient-Specific Finite Element Modeling of Bone from CT Scan Data

Harry B. Skinner, MD, PhD; Joyce H. Keyak, BSME; Christopher E. Cann, PhD; C. Dan Mote, Jr, PhD
VA Medical Center, San Francisco, CA 94121; University of California, San Francisco, CA 94143; University of California, Berkeley, CA 94720

Sponsor: *VA Rehabilitation Research and Development Service (Project #A371-2RA)*

Purpose—The objective of this project is to develop, verify, and document accurate methods for deriving the mechanical properties of inhomogeneous bone from computerized tomography (CT) scan data for the definition of three-dimensional (3-D), patient-specific finite element (FE) models. Several methods of evaluating the mechanical properties of the finite elements will be examined, including a new method based on the hypothesis that orthotropic mechanical properties of an element of bone can be derived by treating each element as a composite of subelements; each subelement would have a modulus computed from the fraction of bone in its volume. The accuracy of the modeling of the bone properties will be determined by comparing the predictions of FE models with the results of mechanical tests of bone specimens.

Methodology—The study is divided into two parts. In Part I, homogeneous specimens of human trabecular bone will be identified, CT-scanned, and mechanically tested. Existing relations for predicting the mechanical behavior of bone using CT scan data will be compared to the measured data. In addition, the new method for deriving orthotropic material properties of the specimens will be developed. This initial phase will establish the accuracy of predicting the behavior of bone of proven homogeneity, so that the techniques can be extended to the FE modeling of inhomogeneous bone.

Part II of the study will involve mechanical testing and FE modeling of inhomogeneous bone specimens. The existing and the newly developed relations for predicting the mechanical properties of bone from CT scan data will be used to generate several FE models of each bone specimen. Each specimen will be mechanically tested and its measured stiffness will be compared with the values predicted by its FE models. The accuracy and precision of each method of FE modeling will be assessed.

Progress/Preliminary Results—Software for automatically generating FE models of bone specimens from CT scan data has been developed. The various methods of computing the mechanical properties of bone will be incorporated into this program. Human tibiae and femora have been obtained for CT scanning/mechanical testing. A method of quantitatively assessing the 3-D homogeneity/inhomogeneity of the trabecular bone has been developed. This method, which uses quantitative computed tomography of the intact bone, is being used to identify regions of homogeneous trabecular bone for Part I of this study. The trabecular bone of the proximal tibia was found to be inhomogeneous; however, the degree of inhomogeneity varied greatly. Regions of relative homogeneity have been identified, and specimens for Part I of this study will be obtained from these regions.

Implications—These findings indicate that isolated specimens of trabecular bone cannot be assumed to be homogeneous. Property data that are obtained from tests of inhomogeneous specimens do not reflect the characteristics throughout the bone sample, and as such, these property data have limited applicability. In addition, the degree of inhomogeneity indicates that the mechanical properties measured from inhomogeneous specimens are highly sensitive to both the size and the precise boundaries of the specimens. These confounding effects can be minimized by using the above method to identify test specimens of the maximum possible homogeneity.

Recent Publications Resulting from This Research

Automated Three-Dimensional Finite Element Modelling of Bone: A New Method. Keyak JH, Meagher JM, Skinner HB, Mote CD, Jr, J Biomed Eng 12(5):389-397, 1990.

[60] Load-Bearing Characteristics of the Wrist with Intercarpal Arthrodesis

Terry R. Light, MD; Julie Wehner, MD; Avinash G. Patwardhan, PhD
Edward Hines, Jr. VA Hospital, Hines IL 60141; Loyola University Medical Center, Maywood, IL 60153

Sponsor: *VA Rehabilitation Research and Development Service (Project #A502-RA)*

Purpose—The specific objective of this study was to define the changes in load-bearing characteristics that occur with selective intercarpal arthrodesis.

Results—Radiocarpal, radioscaphoid, and radiolunate loads have previously been measured in the presence of intact ligaments. Using the model of ligamentous instability suggested by Blevens, et al., scaphoid instability was simulated and radiolunate and radioscaphoid articular loads were judged. In the presence of scaphoid instability, radiocarpal load distribution patterns are similar with both scapho-capitate and scapho-trapezial-trapezoid intercarpal arthrodesis. As in the model without instability, scapho-capitate and scapho-trapezial-trapezoid fusions stiffen the radial column when the scaphoid is in the reduced position. Load is shifted to the radioscaphoid articulation and away from the lunate fossa. The position of the scaphoid within the fusion mass profoundly affects the load transmission across the radioscaphoid and radiolunate surfaces in the presence of instability. Palmarflexion of the scaphoid within the fusion mass unloads the radioscaphoid articular surface. Extension of the scaphoid within the fusion mass unloads the radiolunate articular surface in the presence of instability. Additional investigations are not planned.

[61] Correlation of Streaming Potentials with Stages of Bone Repair/Remodeling

George Van B. Cochran, MD; Bok Y. Lee, MD; Mark Otter, PhD
VA Medical Center, Castle Point, NY 12511; Helen Hayes Hospital, West Haverstraw, NY 10993

Sponsor: *VA Rehabilitation Research and Development Service (Project #A160-3RA)*

Purpose—The processes of bone repair and remodeling are central to the welfare of patients after fractures and/or bone surgery, as well as in conditions ranging from spinal cord injury to osteoporosis, which affect the homeostasis of bone. While bone repair/remodeling is thought to be influenced by mechanical forces, the transducing signal that controls bone cell activity remains undefined. Circumstantial evidence points to mechanically inducted fluid flow in bone, with concomitant production of streaming potentials (SP), also known as stress-generated potentials, as a possible control mechanism. While work on this phenomenon *in vitro* has been in progress for many years, *in vivo* studies of SPs in normal bone have only just begun and nothing is known of their occurrence or characteristics during reparative or resorptive processes. Although various mechanical and/or electrical systems are being developed or are in clinical use in attempts to affect bone healing as well as osteoporosis, the relationship of SPs to these treatment modalities remains unclear. This project aims to define how SPs relate to specific stages and types of bone healing and remodeling, as a step toward determining the clinical significance of these electrical signals.

Progress—The investigators previously developed a model for studying the magnitude and frequency dependence of SPs in living canine tibia using a regime of bending deformation (0.1-40 Hz) applied by a specially designed servohydraulic loading system. The SPs are measured by an improved design of Ag AgCl electrodes suitable for *in vivo* measurements during free walking, and during controlled tibia loading by the servohydraulic system under anesthesia. These techniques are in use in our other current work that seeks to relate existing SP data *in vitro* to *in vivo* conditions, and to study the effects of circulatory, biochemical, and structural factors on SPs in normal intact bone. Certain modifications of the techniques required to make measurements from our healing bone models *in vitro* and *in vivo* were necessary. During the first year of this project, these modifications were successfully completed and tested. Then measurements were initiated and completed on the 3-month series of the "drill hole model" (see Methodology) and work was initiated on the 1-month series. We anticipated all work on the drill hole model being completed as originally scheduled by month 18 of the project.

We also met with our collaborator, Dr. Goodship, and formulated definitive plans for work on our "osteotomy model."

Methodology—Using the techniques described, we measure SPs *in vivo* and *in vitro* on three different models in canine tibia. 1) Drill Hole Model: SP measurements during servohydraulic loading will be made at 2, 4, and 12 weeks during the healing process of 4 mm drill holes in canine tibia. The onset and nature of the SPs produced by bone as it fills the drill holes over time is documented and correlated with histological structure and porosity of the new bone. 2) Osteotomy Model: SP measurements on bone and callus during free walking and programmed servohydraulic loading will be made at 2, 4, and 12 weeks during healing of a 3 mm gap osteotomy stabilized with an external fixator (in collaboration with Dr. Goodship). SPs will be correlated with callus stiffness and histology. SPs also will be measured during several regimens of mechanical loading stimuli applied to the fixator that are thought to be of therapeutic value. Disturbances of the normal electrical patterns of SPs during bone regeneration that may be caused by placement of metallic fixation devices, or by artificial stimulation by microampere currents, will be assessed. 3) Disuse Atrophy Model: After 6-weeks immobilization of one hindlimb, SPs will be measured as a function of the increased porosity of cortical bone in the immobilized tibia, in comparison with the contralateral limb exposed to continued weightbearing.

Results—Preliminary indications suggest that SPs from healing bone (3-month-old drill holes) may be larger than SPs from normal cortical bone. Data analysis on this first series of the drill hole model is incomplete.

Future Plans/Implications—This study represents a natural extension of our prior work on electrical stimulation of bone and on stresses at the bone implant interface, but with a new direction: characterization of SPs at specific clinical stages of bone repair/remodeling. This project joins our on-going studies in a two-pronged effort to understand the clinical significance of SPs and to use this knowledge to therapeutic advantage. This project has high significance with reference to surgical procedures, wound healing, and bony fixation of internal joints/prosthesis, as well as to all orthopedic surgical and rehabilitative treatment of musculoskeletal and neurological disorders in the aging veteran.

[62] In Vivo and In Vitro Mechanical Behavior of the Normal and Degenerated Lumbar Spine

Dan M. Spengler, MD; Tony S. Keller, PhD
VA Medical Center, Nashville, TN 37212-2637

Sponsor: *VA Rehabilitation Research and Development Service (Project #A095-4RA)*

Purpose—The objective of this study was to characterize the static and dynamic load-sharing capability of the normal and degenerated lumbar spine unit. Analysis of the results will focus on the: 1) interdependence between disc and vertebral body properties; 2) degenerative conditions which compromise normal function; 3) development of clinical assessment techniques for predicting the mechanical condition of the human lumbar spine; and, most importantly, 4) role of mechanical dysfunction in chronic low back and sciatic pain. Based on these results, risk criteria will be developed for the management and prevention of low back disorders.

Progress—Chronic animal studies were designed to assess the chronic *in vivo* mechanical behavior of adult porcine spinal units following three-level rigid fixation and semirigid (constant load) vertebral body fixation. *In vitro* mechanical and morphological studies of human vertebrae were designed to characterize the material and structural heterogeneity within the centrum and anterior longitudinal ligament (ALL).

Methodology—A specially designed loading apparatus was used to apply *in vivo* compressive loads to the porcine vertebral unit via pins inserted into the L1 and L3 vertebral bodies. Creep-recovery curves and cyclic load-deformation curves were obtained prior to and 1 to 4 months post surgery in a total of 16 animals. Anterior-posterior variations in the compressive stiffness of the vertebral end-plate were assessed along the saggital plane using a specially constructed "continuous contact" loading apparatus, and the results were compared to saggital plane variations in trabecular morphology and intervertebral disc hydration. The tensile mechanical properties of the human ALL were assessed using a real-time motion analysis system which recorded the displacement of markers attached to the ligament substance and insertions.

Results—Comparison of the static (creep) and dynamic (cyclic) mechanical behavior of the chronic posterior fixation groups indicated that there was a significant decrease in creep rate and increase in stiffness in animals with rigid or semirigid fixation devices. The semirigid (constant force spring) fixation group, however, exhibited a lower stiffness and higher creep rate than the rigid (plate) fixation group, suggesting that less rigid fixation devices can provide a more graded fusion response.

Analysis of the trabecular morphology within the human vertebral centrum revealed a highly heterogenic distribution of trabecular bone in terms of stiffness, porosity, and orientation, suggesting that a heterogeneic distribution of trabecular material should be used for analytical studies of the human spine. In addition, a close correlation between the compressive mechanical properties of the vertebral end-plate and disc properties was found, suggesting that an interdependence of disc and bone properties exists which is hypothesized to be an adaptive response to differences in disc pressure in normal and degenerated segments.

Large variations in regional strains in the ALL were found, with the highest strains in the outer part of the ligament. The mode of ligament failure was also correlated to the vertebral density, suggesting that ligament structure and function are closely correlated to bone structure and function.

Future Plans—We are currently developing three-dimensional, anatomically correct finite element models of the human lumbar spine from CT data, MRI images, and tissue sections, and plan to develop analytical models which can be used to predict loads on the spine based upon force plate and skeletal accelerometer data. These models will be used to predict the mechanical behavior of the spine following aging, disease, injury, and surgical interventions. Longer-term chronic animal studies are also being planned and will include studies of biological fixation and bone remodeling using flexible or "ideal" stiffness anterior and posterior vertebral prostheses.

Recent Publications Resulting from This Research

Flexible Device for Vertebral Body Replacement. Main JA et al., J Biomed Eng 11:113-117, 1989.

In vivo Creep Behavior of the Normal and Degenerated Porcine Intervertebral Disc: A Preliminary Report. Keller TS et al., J Spinal Disord 1:267-268, 1989.

Regional Variations in the Compressive Properties of Lumbar Vertebral Trabeculae. Keller TS et al., Spine (European edition) 14:1012-1019, 1989.

Young's Modulus, Strength and Tissue Physical Properties of Human Compact Bone. Keller TS, Mao Z, Spengler DM, J Orthop Res 8:592-603, 1990.

The Dependence of Intervertebral Disc Mechanical Properties on Physiological Conditions. Keller TS et al., Spine (European edition) (in press).

Patents

Dynamic Vertebral Prosthesis. Patent Number: 4,932,975.

[63] Contact Pressure in the Hindfoot

Bruce J. Sangeorzan, MD; Allan F. Tencer, PhD; Ulrich Wagner, MD; Richard M. Harrington, MS
VA Medical Center, Seattle, WA 98108; University of Washington Department of Orthopaedics, Seattle, WA 98195

Sponsor: *VA Rehabilitation Research and Development Service (Project #A553-RA)*

Purpose—The purpose of this study is to determine normative data on contact pressures in the human subtalar joint. This will then be used as a basis for further studies on pathological conditions and the investigation of our rationale of treatment for them. The specific pathological circumstances to be investigated include talar neck fractures, calcaneus fractures, and ligament injuries.

Progress—A loading system was developed and three circumstances were studied. First, the posterior facet alone was loaded through the tibia. The posterior facet was used because it is the largest, most accessible and the most important. The load delivered through the tibia since this is the method used in other studies of this nature. We next repeated the study with the fibula under load as well and found that the significant loading differences occurred. We then applied load through the tibia and fibula and added transducers in the anterior/middle facet. No change occurred in the pressures or areas in the posterior facet with the addition of the transducers in the middle/anterior facet. We evaluated this as a measure of the disturbance in specimen stability with the additional dissection required to gain access to the other facets.

Methodology—Fresh frozen cadaver specimens including a foot and 10 to 20 cm of distal tibia were used. Preparation of the specimen was done so as to maintain the integrity of joints. The posterior facet was approached posteriorly and the middle/anterior facet was approached medially. A loading apparatus holds the tibia while allowing the foot to move freely during application of loads up to 1400 N. The upper surface of the plate on which the foot rests can be adjusted to 10 degrees of hindfoot inversion or eversion. The amount of load applied to the fibula is monitored and adjusted from 0% to 20% of total applied load. Two Steinmann pins are inserted in the tibia, talus, and calcaneus to serve as the bases for a reference coordinate system in each bone. The coordinates of two points on each pin are located using a digitizing system based on rotary (RVDT) and linear variable differential transformers (LVDT). Displacement and angular position data are sampled using an analog-to-digital convertor interfaced to a computer. Relative translations and rotation between tibia and talus, and talus and calcaneus are calculated using custom software.

Pressure-sensitive film (Fuji Prescale) is used in the pressure measurement system. Dies corresponding to the shape of the joint surfaces are used to cut pieces of film which are sealed in waterproof tape. The film is positioned in the joint space before loads are applied to the foot. Pressure causes dye-filled microspheres in one layer of film to break and be absorbed by the second layer of film. A video camera interfaced to a digitizing board is used to scan the film and calibration strips. A color map is produced on the computer monitor corresponding to the contact area and pressure distribution on the joint surface. The total contact area, overall average pressure, coordinates of the centroid of the contact area, and the zone of peak pressure can be calculated.

Results/Implications—Thirteen normal specimens have been tested. Analyses are currently being completed on pressure distribution and kinematics, and on the role of the fibula in load distribution in the normal subtalar joint. In general, the medial and anterior parts of the posterior facet were the most loaded regions. The overall contact areas increased with increasing loads. The high pressure zone increased more than the overall contact areas at the higher loads. In inversion, the overall contact area/joint area was significantly less than in the neutral or everted position. Unlike the posterior facet, the contact areas in the anterior facet are not dependent on the inversion or eversion of the hindfoot. Though the contact areas and high pressure area ratios do increase from the 350 N to 700 N loads, they are not increased by further loads. These results indicate that the hindfoot is less tolerant of the inverted position than of neutral or everted position. Further, these data provide a background against which pathological alterations of the joint may be measured.

[64] Finger-Force and Motion Apparatus

P.H. Sutter; Nitish V. Thakor
Franklin and Marshall College, Lancaster, PA 17604; Department of Biomedical Engineering, The Johns Hopkins School of Medicine, Baltimore, MD 21205

Sponsor: *Dana Foundation*

Purpose—The purpose of this study was the development and use of apparatus to measure the force exerted by fingers and their motion in opposition to computer-controlled force and motion.

Progress/Methodology—We have constructed a computer-controlled motor-drive apparatus which measures the force exerted by a finger and the angular position of the finger. The data is digitized and stored as a function of time in the computer. The computer also exerts a programmable force and provides programmable position control. A semiconductor load cell moves in a circular arc as it is pushed on by a finger and measures reaction force on the finger.

We investigated flexure forces of the index, long, and ring fingers of subjects in opposition to the motor-drive load cell. In one application, a subject exerts maximum force against the load cell as the device sweeps through a range of angles under computer control. This yields force as a function of angular position during motion at controlled rates. In other experiments, the subject exerts a target force against the computer-controlled device, testing the ability of the subject to sense and control the force. The device can be programmed to provide a reaction force that is a function of time or of position; for example, it can simulate pushing against a spring. The device can be used to measure finger force and motion or to provide controlled exercise. It has been used to study the kinesthetic perception of force and the ability to control the force exerted by fingers. It has also been used to study forces resulting from the stimulation of muscles.

Recent Publications Resulting from This Research

Reflected-Force Feedback to Fingers in Teleoperations. Sutter PH, Iatridis JC, Thakor NV, in Proceedings of the NASA Conference on Space Telerobotics, Pasadena, CA, IV:65-74, 1989.

[65] Quantitative Functional Anatomy of the Human Shoulder

R.H. Rozendal; H.E.J. Veeger; L.H.V. van der Woude; G. Pronk; F. van der Helm
Department of Functional Anatomy, Faculty of Human Movement Sciences, The Free University, 1081 BT Amsterdam, The Netherlands; Department of Cybernetical Ergonomy, Technical University, 2600 AA Delft, The Netherlands

Sponsor: *Innovative Research Programme/Aids for the Handicapped*

Purpose—Quantitative data on the musculoskeletal system of shoulder and arm are needed with a view to: 1) analysis of movements of shoulder girdle and arm, based on arm movement registration in activities such as wheelchair driving; 2) analysis of movements of the shoulder girdle and arm in activities of daily living (ADL) and vocational activities; 3) predictions of outcome of arthrodesis of the shoulder in patients with a lesion of the brachial plexus; and, 4) aiding interpretation of *in vivo* human palpation data.

Methodology/Results—The cadaver measurement data were used to run a model which is based on finite element analysis and comprised a dynamic version of this method (SPACAR). The model was used to describe the movements of the bones of the shoulder girdle and arm with respect to each other and with the trunk. The data on muscles were analyzed: the estimated physiological transsections correlated well with muscle mass with some exceptions. Left/right differences were not found.

The accuracy of the model was tested. The location of the center of rotation of the humeral head was computed. The function of the coracoclavicular connections was analyzed from earlier determinations of the position of the bones of the girdle in relation to each other and to the trunk in various positions of the arm. The model was validated on values taken from patients with arthrodesis of the shoulder. Studies on the efficiency of muscular work while driving a hand-rim propelled wheelchair ergometer were conducted.

Future Plans—Use of the model in ergonomic problems is planned.

[66] Biomechanical Modeling for 3-D Analysis of Lifting

Carlo Frigo, Dr; Umberto Saraval, Dr; Antonio Pedotti, Prof
Centro di Bioingegneria, Politecnico di Milano, 20148 Milano, Italy

Sponsor: *Italian Ministry for University and Scientific Research*

Purpose—The purpose of this project is to achieve a comprehensive description of kinematics and loads on the spine in regard to manual material handling. The work is aimed at analyzing different lifting techniques in which the dynamic factors and the rotation of the trunk play an important role.

Progress—A model of the human body consisting of the head, trunk, upper arms and fore-arms, pelvis and lower limbs, has been implemented on a computer. The inverse dynamics problem has been solved for the anatomical segments above the lumbar tract, and forces and movements have been computed in relation to an intervertebral disk that can be selected between L3/L4 and L5/S1.

The model was tested by a sensitivity analysis in which the different anthropometric and dynamic factors have been changed to observe their influence on the final results. A validation of the model has been made by analyzing simple movements in the sagittal plane (the only ones described in the literature), and by comparison of the results. Preliminary investigations on different subjects and different lifting techniques has begun.

Methodology—The main instrumentation adopted for this study is a motion analyzer based on the elaboration of signals from two TV cameras. Reflective markers are arranged on the subject in such a way that each anatomical segment considered can be identified by at least three nonaligned points. A force platform is used for measuring the external forces acting on the load. A schematization of the body segments is made on the basis of the rigid body theory. Three-dimensional (3-D) description of body movement is achieved by considering the translatory components of the movement of each center of mass, and the rotation of each segment, by means of the Euler angles. No reactions at the lumbar intervertebral disks are computed by solving the inverse dynamics problem. The compression force on the disk is obtained by a simple schematization of the musculoskeletal structure based on the concept of the muscle equivalent.

Results—A comparison between the spinal loads computed by a static method and those obtained dynamically has shown that in some circumstances the compression force on the intervertebral disk can be as high as 2.4 times the load computed statically. Furthermore, the shearing force on the disk is not negligible, and due to the inadequacy of the disk to sustain shearing forces they must be closely monitored. The model schematization results from a sensitivity analysis that the orientation of the disk is one of the most important parameters for the estimation of normal and transverse components. Thus it is imperative to obtain reliable data on the disk orientation in the different phases of movement.

Future Plans—We plan to improve the model as a tool for predicting spine loads by: 1) an investigation into the relation between the external measurements and orientation of the intervertebral disk surface; 2) better definition of the anthropometric parameters (such as the mass and movements of inertia) of the different body segments; 3) an analysis of the role of muscles and passive structure at the lumbar level, and implementation of new algorithms to predict how the forces are shared between them; and, 4) investigation of the role of intra-abdominal pressure.

Recent Publications Resulting from This Research

Valutazione Biomeccanica dei Carichi Sulla Colonna Vertebrale Mediante Modello Tridimensionale. Frigo C et al., in Proceedings of the International Seminar "Lavoro e Patologia del Rachide," Milano, 1989.

Three-Dimensional Model for Studying the Dynamic Loads on the Spine During Lifting. Frigo C, Clin Biomech 5:143-152, 1990.

A Three-Dimensional Model for Spinal Load Computation in Dynamic Conditions. Frigo C, in Proceedings of the First World Congress of Biomechanics, San Diego, 1990.

[67] Evaluation of Osteoporosis by Ultrasound, CAT Scan, and Photon Absorptiometry

Subrata Saha, PhD; J.A. Albright, MD
Department of Orthopaedic Surgery, Louisiana State University Medical Center, Shreveport, LA 71130

Sponsor: *Louisiana State University Medical Center, Center of Excellence for Arthritis and Rheumatology*

Purpose—The diagnosis of advanced osteoporosis may be based on changes in the bone density, and/or by measuring cortical bone thickness, both of which are generally determined from roentgenological examination of bone. However, the roentgenological evaluation of osteoporosis is qualitative in nature, and it requires a minimum bone loss of 30% before an unequivocal roentgenological diagnosis of osteoporosis can be made. The aim of this study was to determine if cortical bone thickness and bone density can be measured accurately by ultrasound, computer-aided tomography (CAT) scan, and photon absorptiometry, and to compare their relative sensitivity.

Methodology—The cortical bone thickness and bone densities were measured at 16 locations of each femur using a computer tomography (CT) unit (Ohio-2020, Technicare). Thicknesses at the same locations were then measured by ultrasound using the pulse-echo technique. An immersion-type transducer (Dapco, S1H5) was used at a frequency of 5 mHz with a pulse-repetition frequency of 100 Hz. Both the specimen and the transducer were immersed in a water tank. Once these ultrasonic measurements were completed, the bones were sectioned, and the actual thicknesses at the same locations were measured with a micrometer. The bone densities at each location were also determined.

Progress—Cortical bone thickness and bone densities of embalmed human femurs and tibiae have been measured by ultrasound, CT, and photon absorptiometry. Fresh and embalmed human vertebrae and pelvis have also been evaluated similarly.

Results—The individual micrometer measurements made on 48 locations were compared with the corresponding ultrasound and CT data. The correlation coefficients between the actual thickness and the ultrasonically-measured thickness was 0.95, and 0.62 with the CT. We attribute the error in the CT data partly to the technique involved in the measurement (it can read only integral numbers) as well as to the subjective nature in selecting bone edges, and thus in positioning the electronic cursors. Variations between the actual bone densities for these samples were minimal, and it did not show significant correlations with the attenuation of ultrasound.

The results of the *in vitro* study suggest that ultrasonic measurement of cortical thickness is more accurate than similar measurement by CT. Moreover, ultrasound does not use ionizing radiation, and it is significantly cheaper to use than the CT. Thus, ultrasound technique, when fully developed, may be more suitable for large scale screening for osteoporosis.

Future Plans—This study is being continued in order to compare the relative accuracy of ultrasound, CT, and photon absorptiometry methods in evaluating osteoporosis. Other mechanical methods, such as bone vibration, are also being developed as a means to quantify the integrity of bone *in vivo.*

Recent Publications Resulting from This Research

Ultrasonic and Vibration Methods to Measure In Vivo Bone Properties. Saha S, invited paper, presented at the ASME Winter Annual Meeting, 1989.

Bone Mineral Content and Load Carrying Capacity of Whole Bones (Abstract). Saha S et al., Abstracts of the First World Congress on Biomechanics, I:208, 1990.

[68] Establishing the Reliability and Validity of an X-Ray Measure for Shoulder Subluxation

Elizabeth Boyd, MSc(OT); Micheal D. O'Riain, PhD, PEng; Louis Goudreau, PEng, BSc; Anne Gaylard, BA(OT); Dianna Grinnell, MD, FRCP(C); George Torrance, PhD; Lynn Mortimer, BASC; Penny Pepin, BSc(OT); Helene Lauzon, BSc
Department of Rehabilitation Engineering, The Rehabilitation Centre, Ottawa, Ontario K1H 8M2 Canada

Sponsor: *National Health Research and Development Programme, Department of Health and Welfare, Canada*

Purpose—The objective of this study is to test the reliability and validity of a new X-ray method of measuring shoulder subluxation. The method involves positioning the patient in a specially constructed chair and taking an X-ray from a standardized position. This will produce a uniform film from which angles and distances can be measured with precision.

Specifically, we will test: 1) the construct validity of the X-ray method by comparing the measurements obtained for patients with clinically-subluxed shoulders to those without any clinical signs of subluxation; 2) the concurrent validity of the X-ray method by comparing measurements obtained of subluxed shoulders with occupational therapist's clinical measures of shoulder subluxation; 3) the inter-rater reliability of positioning the patient in the chair by having two teams of therapists position patients and comparing the measurements obtained from X-rays of a patient's subluxed shoulder; 4) the intra-rater reliability of positioning the patient in the chair by having the same team of therapists position patients twice and comparing the measurements obtained from X-rays of a patient's subluxed shoulder; 5) the inter-rater reliability of the X-ray reading by comparing measurements made by four therapists from a single X-ray; and, 6) the intra-rater reliability of the X-ray reading by comparing measurements made twice by a therapist from a single X-ray.

Progress/Methodology—Data was collected from 36 stroke patients who have subluxation on clinical examination, and 36 patients who do not. Patients who do not have subluxation participated in the validation phase (Objective 1). Patients who have a subluxation participated in the validity and inter- and intra-rater reliability studies (Objectives 2 to 6). Patients exhibiting a subluxed shoulder on clinical examination were randomly allocated to participate in either the inter-rater or intra-rater study. Patients in whom inter-rater reliability was to be assessed were positioned for X-ray by each of two teams of therapists with a rest interval. Patients in whom intra-rater reliability was to be assessed were positioned twice by the same team of therapists with a rest interval.

The dependent variables, distance and angle of subluxation, were measured on a ratio scale. If the values obtained from the X-ray readings were normally distributed, then parametric statistics like the *T*-test, analysis of variance F test, Pearson's, or intraclass correlation coefficients can be used to test the hypothesis.

Preliminary Results/Implications—An interim data analysis using the data from 12 subjects with subluxation and 12 subjects without subluxation was completed in August 1989. Results of this preliminary analysis indicate that the X-ray measure is reliable and valid. Establishing the reliability of the measure will permit needed research into the effectiveness of therapeutic interventions for subluxation. Specifically, the effectiveness of shoulder supports commonly used in the treatment and prevention of subluxation may be investigated.

[69] Harvard–Massachusetts Institute of Technology Rehabilitation Engineering Center

Robert W. Mann, ScD
Newman Laboratory for Biomechanics and Human Rehabilitation, Mechanical Engineering Department, Massachusetts Institute of Technology, Cambridge, MA 02139

Sponsor: *National Institute on Disability and Rehabilitation Research*

Purpose—The Harvard-MIT REC addresses the NIDRR Research Priority "Quantification of Human Physical Performance." Seven collaborative, interdisciplinary projects (listed below) involve rehabilitation engineering research personnel at the MIT Newman Laboratory for Biomechanics and Human Rehabilitation and clinical rehabilitation research personnel at the Biomotion Laboratory of the Massachusetts General Hospital and at the Veterans Administration Medical Centers at West Roxbury/Brockton and Jamaica Plain.

- Computer-Aided Surgical Simulation of Femoral and Tibial Osteotomy
- Patient Management and Rehabilitation Protocols Following Major Hip Surgery Based on Quantitative *In Vivo* Data
- Quantification of Human Motor System Adaptation and the Ability to Use Hand Tools by Upper Extremity Amputees
- Quantitative Assessment of Functional Electrical Stimulated Grasp Devices Using a Human Interactive Hardware Simulator Approach
- A Force and Movement Transduction System for Diagnosis and Treatment of Movement Disorders
- Multi-Degree-of-Freedom Manipulandum for Characterization of Motor Function and Optimization of Assistive Technology
- Quantitative Assessment of Posture and Balance Abnormalities.

All projects stress developing and evaluating scientifically-based, quantitative methods for assessing the physical status of handicapped persons and of therapeutic efforts for defect remediation. Different projects address medical interventions, including orthopaedic surgery and physical therapy, and/or augmentative technology, including amputation prostheses, orthoses, and functional neuromuscular stimulation.

A theme common to all projects is the use of human-interactive computer-based systems for functional assessment of disability status. When employed diagnostically, such systems present performance criteria and data via "friendly" computer interfaces to the physician, rehabilitator, and/or subject. When the consequences of differential therapy are being evaluated, such systems emulate alternative assistive technologies using special-purpose hardware in conjunction with the computer system, thereby achieving physical interaction with the disabled person. Such quantitative assessment can critique, augment, and enhance more common and prevalent qualitative, subjective, medical, and rehabilitation assessments. Inherent in our approach is the conviction that mathematically expressible (and therefore, computer-manageable) models of augmentative technology, of aspects the disabled human and of device-human interaction can help diagnose the extent and character of disability and better define and evaluate proposed rehabilitation protocols and technology. All studies are directed toward practical augmentative technology and/or improved rehabilitation diagnosis and therapy.

Specific projects reported on in this issue are: "Measurement of the Degrees of Freedom of the Normal Human Knee *In Vivo,*" and "Using Axodes to Compare *In Vivo* Knee Kinematics Measured Using Bone versus

Skin-Mounted Markers," in Chapter II, A. Bone and Joint Studies; "Quantification and Display of Musculoskeletal Anatomy," "Mobility Analysis," and "Musculoskeletal Modelling," in Chapter II, B. Human Locomotion and Gait Training; and, "Correlation of *In Vivo* Synovial Joint Pressure Data With That From Posthumous Hemipelvis and Proximal Femur Including Pressure-Instrumented Endoprosthesis," in Chapter XI, Orthopedic Implants, B. Hip.

[70] Computer-Aided Surgical Simulation of Femoral and Tibial Osteotomy

Derek Rowell, PhD; Robert W. Mann, ScD; W. Andrew Hodge, MD
Newman Laboratory for Biomechanics and Human Rehabilitation, Mechanical Engineering Department, Massachusetts Institute of Technology, Cambridge, MA 02139

Sponsor: *National Institute on Disability and Rehabilitation Research*

Purpose—In the hip joint, the degeneration of cartilage, synonymous with osteoarthritis, is usually focal and located on the superior region of the femoral head where it articulates with the acetabulum, the area loaded during the stance phase of normal level walking. In intertrochanteric osteotomy, the proximal section of the femur is transected and reoriented to move an area of good cartilage into the load-bearing region. The average 12-year life of total hip replacement has renewed interest in osteotomy since it is intrinsically conservative of joint tissue, compared with total replacement where the removal of much natural bone and the use of acrylic cement makes revision difficult. For the younger patient, a successful osteotomy can provide 5, 10, or more years of service before partial or total hip replacement is necessary. At the knee, proximal tibial osteotomy is indicated in patients with osteoarthritis of one tibiofemoral compartment producing varus or valgus deformity.

Methodology—The preoperative planning of either osteotomy procedure poses a substantial geometric and functional challenge to the orthopaedic surgeon. In current practice, planning is based on, at the most, biplanar X-rays of the affected region. Using a protractor, ruler, and grease pencil, the orthopaedic surgeon sketches on the two-dimensional X-rays a geometrical design of what is intrinsically a three-dimensional manipulation. In addition to the primary goal of cutting and reconnecting the fragments of the proximal femur or tibia to bring good cartilage into proper load-bearing, the surgeon must also ascertain that the proposed alteration will cause minimal interference with the normal ranges of motion about the joint. Further, he/she must be confident that the alteration or reorientation of the bone components has not significantly lengthened or shortened the skeleton across the joint, considering also the possible alteration of the effective muscle or ligament lengths. Ultimately, the surgeon must be concerned with how the operation will affect, and hopefully improve, the mobility and grace of the subject in tasks such as normal level walking, stair-climbing, rising from a chair, etc. The magnitude and complexity of this design task undoubtedly explains, in part, the uncertain outcome of the procedure and represents a deterrence to more widespread practice of osteotomy.

Computer-Aided Surgical Simulation (CASS), addresses this surgical design problem as prototypical of many musculoskeletal alterations practiced in orthopaedic surgery. CASS borrows from the now well-established field of computer-aided design (CAD), adopting both commercially-available computer hardware and graphic display terminals and reinterpreting and augmenting CAD software.

Observation of surgeons and practice in orthopaedics suggests that the engineer-designer and the orthopaedic practitioner have much in common. They observe the circumstances of the situation and devise an idea for a solution. Whereas the engineer-designer now can carry out the exploration, iteration, and optimization of design concepts in consort with the computer, the surgeon practitioner is constrained to a single solution, the particular surgical procedure performed in the operating room, and then must await the recovery of the patient to observe the consequences. Validation is uncertain since many procedures are very patient-specific. Even with similar procedures, the surgeon must follow a series of patients before evaluation of outcome is possible.

In some aspects, CASS is significantly different from CAD. Whereas the engineer designs *de novo*, the surgeon must deal *a priori* with the patient-specific, complex geometry of the relevant skeletal anatomy. The surgeon devises a plan to sever, realign, and reconnect these anatomical parts, then wants to explore the consequences of the changes, compared to the preoperative state of the patient. A further major distinction between the design engineer with a CAD system, and a surgeon simulating a procedure on the patient's anatomy with the CASS system, is the background and experience the respective operators bring to the computer system. The engineer is fluent in the geometric, mathematical, and physical implications of CAD manipulation and is familiar with computer hardware and software. The surgeon's relevant prior experience focuses on direct observation and examination of the patient and studying the X-rays. Therefore, the computer's graphic display must present anatomy and mobility to the surgeon in a manner consistent with his or her prior experience; and the means by which the surgeon manipulates the display and interprets the consequences of changes must be as traditional and easy to learn as possible.

Results—Overall, CASS can be subdivided into three tasks: mobility analysis for presimulation recording and presentation of user-friendly, easily manipulatable and interpretable dynamic displays of the patient's movement patterns; patient-specific anatomical representations for the computer displays on which the surgeon will simulate and evaluate the procedure, and for the determination of body segment mass and inertial properties for dynamic analyses; and musculoskeletal modelling for the detailed mathematical representation of the skeletal, joint, and muscle system for pre- and post-simulation evaluation. These tasks are described as separate projects.

[71] Studies of the Strength Parameters in the Vertebral Body

Joseph Mizrahi, DSc; Wilson C. Hayes, PhD; W. Tom Edwards
Orthopaedic Biomechanics Laboratory, Beth Israel Hospital and Harvard Medical School, Boston, MA 02115; Technion—Israel Institute of Technology, Haifa, Israel; State University of New York Health Science Center, Syracuse, NY 13210

Sponsor: *National Institutes of Health; M.E. Mueller Fellowship and the M.E. Mueller Professorship in Biomechanics at Harvard Medical School*

Purpose—The goal was to study parametrically the geometric and constitutive properties influencing vertebral strength and to identify the biomechanical parameters which are most critical to vertebral failure.

Progress/Methodology—A three-dimensional (3D) finite-element (FE) model of the third lumbar vertebral body was developed, including two major material groups: cancellous bone for the centrum, and cortical bone for the cortical shell and endplates.

To study the effects of geometric, material, and loading parameters, models were created as follows: 1) refinement of the initial geometry, including: *a*) a tear-drop cross section corresponding to the frontal and sagittal diameters; *b*) inward sloping of the side walls to represent tapering; and, *c*) biconcavity of the vertebral body. Each of these changes was made by using analytical approximations to alter the coordinates of the 3D mesh; 2) stiffening of the cortex in the central third of the posterior wall to simulate the presence of the posterior elements; 3) regional variation of the modulus of elasticity of the cancellous region, in correspondence with quantitative computed tomography data; 4) separate reductions of the moduli of the cortical, cancellous and endplate regions, followed by parallel reductions of the three moduli, to simulate conditions existing in osteoporosis; and, 5) three loading conditions were studied: uniform, peripheral, and anteriorly eccentric.

The analyses were performed using ADINA, a general displacement-based FE code.

Results—The results obtained are being evaluated in terms of endplate displacement, compressive stress of the cortical shell, and von Mises stresses in the endplate and centrum. The results demonstrate the importance of an accurate description of vertebral geometry. Stiffening of the posterior wall affects the results to a minor extent only. However, when the modulus is reduced for each of the constituents listed above, the displacements and stresses are modified considerably. Information on the overall stiffness of the centrum is found to be more important than that of the regional variations in the stiffness. The loading conditions are found to affect the results obtained, especially the location of maximum displacement.

Future Plans/Implications—It is planned to complete the analysis of the models developed. When complemented by controlled *in vitro* strength testing, the results should allow development of improved predictors of vertebral fracture risk.

[72] Analysis of Strength Reduction Due to Metastatic Defects in the Lumbar Vertebrae

Joseph Mizrahi, DSc; Wilson C. Hayes, PhD
Orthopaedic Biomechanics Laboratory, Beth Israel Hospital and Harvard Medical School, Boston, MA 02115;
Technion—Israel Institute of Technology, Haifa, Israel

Sponsor: *National Institutes of Health; M.E. Mueller Fellowship and the M.E. Mueller Professorship in Biomechanics at Harvard Medical School*

Purpose—To address the problem of strength reductions associated with metastatic lesions in the spine, a three-dimensional (3D) finite-element (FE) model of the vertebral body was developed to study the effects of geometry, material properties, and loading conditions influencing vertebral strength. In this study, we modeled the structural consequences of lytic metastatic lesions under both uniformly distributed and anteriorly eccentric loading. The presence of superimposed osteoporosis was also studied.

Progress/Methodology—The geometry of the lumbar vertebral body modeled included the modified teardrop shape of the cross section, tapering due to inward sloping of the vertebral walls toward the center, and biconcavity of the endplates. Two major material groups were considered: cancellous bone for the centrum, and cortical bone for the cortical shell and endplates. The metastatic defect was modeled in one of two ways: 1) as a prism, symmetrically located about the mid-sagittal plane; or, 2) as a sphere with varying sizes and locations.

To study the combined effect of lesion and general bone loss due to osteoporosis, the latter was first studied alone, with a reduction of the elastic moduli of the cancellous and cortical bone. To simulate a loading condition corresponding to bending forward, an eccentric load distribution was applied to the endplate. The analyses were performed using ADINA, a general displacement-based FE code.

Results—For the prismatic defect alone, the displacement and stresses are shown to increase considerably. However, when combined with osteoporosis and under conditions of eccentric loading, the increase is even more dramatic, with a factor of 8.42 for displacement, and of 3.18 for stress, exceeding the local bone strength.

Future Plans/Implications—It is planned to complete the analysis for the spherical lesion. Additionally, parallel *in vitro* experiments providing experimental data are planned. These should allow us to use our results to develop improved predictions of vertebral failure in the presence of metastatic lesions.

[73] Force and Stability Analysis of the Human Elbow

Kai-Nan An
Mayo Foundation, Rochester, MN 55901

Sponsor: *National Institute of Arthritis and Musculoskeletal and Skin Diseases, National Institutes of Health*

Purpose—The long-term goal of this study is to address the problems of elbow joint dysfunction and reconstructive surgery. Biomechanically, in order to achieve a beneficial surgical outcome, it is important to characterize: 1) mechanical environment and requirements imposed on the elbow joint in daily and recreational activities; and, 2) pathological motion loss, weakness, and instability. This defines the functional impairment to be corrected by reconstructive surgery.

A detailed analysis of the reconstructed elbow joint under these mechanical environments will allow definition of the objective benefits of the surgery and provide a basis for selecting a given procedure.

Methodology—Static and dynamic data on force and position of the upper extremity are acquired by an automatic data analysis system. Electromyographic data are also recorded. Normal test subjects perform a series of routine arm activities. Sophisticated computer models analyze the test results to predict force and torque values.

Progress/Results—Computer software programs have been developed which allow simultaneous collection of motion and load data using the Isotrak system and the Kistler force plate. The kinematics of the joint and the force and moment applied at the joint can then be calculated. The technique has been applied and its reproducibility tested for study of the forces and moments involved in the upper extremities during push-up exercise. The force and moment data at the elbow joint throughout the push-up exercise have been successfully obtained for one subject. Currently, experiments are being carried out on 10 normal, healthy, young male subjects to examine the effects of various factors which may affect performance during this exercise.

An experimental method which uses the Isotrak electromagnetic tracking system has been developed and calibrated for assessment of kinematic and kinetic performance of total elbow joint replacements. This method allows comparison of kinematic and kinetic parameters of the intact normal elbow joint with those of the prosthetic joint. Kinematic parameters include the axis of rotation, joint laxity in valgus-varus and internal-external rotation; kinetic parameters include those of tendon excursion and moment arms of the major elbow flexors and extensors.

Future Plans/Implications—Joint constraint and stability performance will be used to compare the five selected designs of prostheses for elbow joint reconstruction and replacement, each of which is currently available and represents a unique design feature and concept. Experimentally, joint stability or laxity in cadaveric specimens with prosthetic replacements will be quantitated by using the joint kinematic analysis. Elbow joint movement will be achieved with simulated muscle loading as well as additional valgus-varus stress. Changes in the pattern and magnitude of the axes of rotation will be used to assess the joint constraint. In addition, the mechanical advantage of each muscle around the replaced joint will be calculated based on the tendon excursion and joint rotation. Sensitivity analysis will also be performed to analyze the effects of surgical placement of these prostheses and soft tissue reconstruction.

Recent Publications Resulting from This Research

Incorporation of Muscle Architecture into the Muscle Length-Tension Relationship. Kaufman KR, An KN, Chao EYS, J Biomech 22:943-948, 1989.

Physiological Considerations of Muscle Force Through the Elbow Joint. An KN, Kaufman KR, Chao EYS, J Biomech 22:1249-1256, 1989.

[74] Prediction of the Evolution of Bony Architecture

Stephen C. Cowin; Ali M. Sadegh
City College of The City University of New York School of Engineering, Department of Mechanical Engineering, New York, NY 10031

Sponsor: *National Science Foundation*

Purpose—The objective of this research is the development of a finite element computational program for the prediction of the stress adaptation of the trabecular architecture of cancellous bone tissue. A method of predicting the temporal evolution of the trabecular structure of the cancellous bone tissue surrounding a bone prosthesis will contribute significantly to the improved design of bone prostheses, improved surgical placement procedures for implants, the understanding of biological fixation (e.g., porous ingrowth), and to other societal problems, for example, osteoporosis and the effects of long-term space flight. This predictive model is to be based on data consisting of experimentally determined remodeling rate coefficients, and on data generated from human cancellous bone specimens by quantitative stereological and anisotropic elastic constant measurement.

Progress—We are approximately 18 months into the project, and on schedule. Analytical formulation of the model is complete and we have written the computational code. A report of this work has been submitted for publication. This report contains the first model for the prediction of trabecular remodeling in which both the orientation and cross-section of the local trabeculae are considered. It remains only to use the experimental data generated at the University of Michigan to evaluate the remodeling rate constants.

Methodology—Our work is entirely computational and analytical. The data employed was obtained at the University of Michigan.

Results—Development of a model has been completed that permits the prediction of temporal evolution of trabecular architecture when the mechanical loading on the bone tissue is altered as, for example, in the case when a prosthesis is implanted. Some interesting and exceedingly simple results concerning the response of the mid-section of long bones to combined axial and torsional loading have been found. Specifically, it was found that if a thick-walled right circular cylinder capable of surface remodeling is subjected to an axial compressive load and a twisting torque, the remodeling patterns depend on whether the periosteal surface or the endosteal surface controls the limits of the remodeling process. It is shown that the effect of increasing the torque is always opposite to the effect of increasing the compressive load. Thus, similar remodeling patterns are obtained by increasing one type of loading and decreasing the other type of loading. These results were demonstrated in considerable generality, with a minimum of assumptions. Aside from the restriction of idealized cylindrical geometry, the only assumptions are that the bone tissue is linearly elastic and that there exists a finite range of remodeling equilibrium stresses. In particular, the results presented are independent of the specific type of rule governing the temporal evolution of the bone shape.

Future Plans/Implications—Analysis of the experimental data will be completed to determine the remodeling rate coefficients and apply our program to the prediction of the stress adaptation of the trabecular architecture of cancellous bone tissue in simple situations.

Recent Publications Resulting from This Research

A Resolution Restriction for Wolff's Law of Trabecular Architecture. Cowin SC, Bull Hosp Jt Dis Orthop Inst, 49:206-213, 1989.

Errors in the Orientation of the Principal Stress Axes if Bone Tissue is Modeled as Isotropic. Cowin SC, Hart RT, J Biomech 23:349-352, 1990.

Properties of Cortical Bone and the Theory of Bone Remodeling. Cowin SC, in Proceedings of the Symposium on Biomechanics of Diarthrodial Joints, 1st World Congress on Biomechanics, V.C. Mow, A. Radcliffe, S. L-Y. Woo (Eds.), New York: Springer, 1990.

The Structural Adaptation of Bones. Cowin SC, Symposium on Mechanics Applied to Living Organisms, in Proceedings of the 11th U.S. National Congress of Applied Mechanics. Appl Mech Rev 43S:126-133, 1990.

Candidates for the Mechanosensory System in Bone. Cowin SC, Moss-Salentijn L, Moss ML, J Biomech Eng (accepted for publication).

The Mean Intercept Length Polygons for Systems of Planar Nets. Luo GM, Sadegh AM, Cowin SC, J Materials Sci (accepted for publication).

A Note on the Anisotropy and Fabric of Highly Porous Materials. Cowin SC, J Materials Sci (accepted for publication).

The Proportional Elastic Invariants for Anisotropic Materials. Sadegh AM, Cowin SC, J Appl Mech (accepted for publication).

[75] Growth of Cartilage In Vitro: The Role of Mechanical Factors

Martha L. Gray; J.W. Kieckhefer; A. Minerva Garcia
Continuum Electromechanics Group, Laboratory for Electrical and Electronic Systems, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology and Harvard-MIT Division of Health Sciences and Technology, Cambridge, MA 02139

Sponsor: *National Science Foundation*

Purpose—The long-term objective of our research effort is to identify the mechanical factors which are important in regulating cartilage growth and remodeling, and to elucidate the cellular mechanisms by which mechanically-mediated growth and remodeling occur. While abundant *in vivo* experimental and clinical evidence suggests that mechanical factors play an important role in mediating growth, the phenomenological nature of existing data make it difficult to identify how specific features of mechanical loading affect cellular behavior and, consequently, tissue growth. The research here exploits an *in vitro* model system—the neonatal rat mandibular condyle—in which tissue growth occurs to examine the direct relationship between applied loads and tissue growth and biosynthesis.

Progress/Methodology—Progress to date includes primarily baseline studies of growth and biosynthesis under free-growing (not mechanically-loaded) conditions. We are developing systems in which the physical environment can be reliably and quantitatively controlled.

Mandibular condyles are harvested aseptically from 2-day-old Sprague-Dawley rats and maintained in culture with daily medium changes. The "biological state" is determined from a combination of morphological and biochemical assays. *Size:* Specimen length and diameter is determined daily in unloaded specimens using photomicroscopy. Loaded specimen length is continuously measured as the displacement of the loading platen. *Synthetic Rate:* The incorporation of radioactive precursors over a 2- to 12-hour period is assessed using standard techniques: ^3H-thymidine for cell proliferation by DNA synthesis; ^{35}S-sulfate for glycosaminoglycan (GAG) synthesis; and ^3H-proline for protein synthesis. *Tissue Composition:* DNA and GAG content is determined, respectively, from the Hoechst 33258 and dimethylmethylene blue dye binding assays.

Rat condyles ($N>100$) have been explanted and maintained unloaded in culture for up to 5 weeks. The condyles increased in length at a rate of $\sim$120μm/day for the first week, and $\sim$60μm/day for the remaining 4 weeks. Commensurate increases in wet weight and GAG content were observed; the GAG content normalized to weight remained approximately constant in time, suggesting that the increase in length was achieved by production of a normal GAG-containing matrix. DNA content increased progressively with time in culture, although the proportional increases were not as large as for GAG and tissue weight. GAG synthesis rates were relatively constant over the 5-week period, consistent with the constant increase in tissue GAG content. Parallel studies with serum supplemented medium (1% FBS) showed essentially identical results, suggesting that factors present in serum do not significantly affect tissue growth.

A loading device has been designed, constructed, and tested. It is a major improvement over previously reported devices because it allows the condyles to be subjected to constant (but adjustable) force, independent of condyle length. Condyle length is monitored continuously using a capacitive displacement measurement. Studies of condyles subjected to constant load are ongoing.

Future Plans/Implications—This research is directed at understanding the role of mechanical forces in the growth of skeletal tissues. The direct relationship between the observed macroscopic growth and biochemical parameters suggests this condyle system will be a very useful model in which nondestructive observations of the response to mechanical perturbations can be made. In order to achieve our ultimate objective of discerning the physical and biological mechanisms involved in mechanically-mediated growth, ongoing and future studies will allow comparison of the growth response to several types of physical stimulation. A complete understanding of this would allow us to predict tissue composition and morphology for given loading conditions. This clearly has implications to our understanding of physiological and pathophysiological growth processes, and to the development of therapeutic modalities.

[76] Electrical Properties of Wet Bone as a Function of Frequency and Microstructure

Subrata Saha, PhD; Paul A. Williams, BS
Department of Orthopaedic Surgery, Louisiana State University Medical Center, Shreveport, LA 71130

Sponsor: *National Science Foundation*

Purpose—Electrical properties of fresh human bone have not been characterized for all three principal directions and for a wide range of frequency. In this project, we plan to measure the electric and dielectric properties (the specific resistance, specific capacitance, complex dielectric constant, and the loss factor) of fresh human compact and cancellous bones in the three principal directions and for a frequency range of 5 Hz to 10 MHz. The measured electrical properties will be correlated with the microstructure, density, and mineral content of the bone samples.

Methodology—Specimens from above-knee and below-knee amputations were obtained shortly after pathological examination and had been maintained under refrigeration from post-surgery until examination. All soft tissue was removed, the bones wrapped, and stored in a freezer. The frozen specimens would then be thawed, unwrapped, machined, and tested without being allowed to dry. Electrical and physical properties were measured with small samples being saved for histological processing. Electrical measurements were made using LCR meters (HP 4275A and HP 4262A) with measurements being made in all three orthogonal directions.

Results—All electrical and dielectric properties except the resistivity and the impedance were highly frequency dependent for the frequency range tested. All electrical and dielectric properties were transversely isotropic as the values for the longitudinal direction were different from values obtained for the two transverse directions, and properties in the two transverse directions were approximately similar.

Progress—Preliminary studies have been completed to determine the validity of the proposed method of measurement. Use of different types of electrodes have been tested in order to minimize the electrode polarization effect. Measurement of the electrical properties of some human compact and cancellous bone samples have also been completed. The information on the electric and dielectric properties of bone obtained from this study will be helpful to: 1) analyze the current distribution amongst different tissues when electrical stimulation is applied for osteogenesis; 2) develop a mathematical model for the electromechanical behavior of bone; and, 3) optimize a previously developed noncontacting electromagnetic device for monitoring the *in vivo* properties of bone.

Recent Publications Resulting from This Research

Electrical Properties of Demineralized Bone. Saha S et al., Digest of Papers: Eighth Southern Biomedical Engineering Conference, 147-149, 1989.

Electric and Dielectric Properties of Wet Human Cancellous Bone as a Function of Frequency. Saha S, Williams PA, Ann Biomed Eng 17:143-158, 1989.

[77] Nondestructive Surface Detection of Cartilage Degeneration via Electromechanical Spectroscopy

Alan J. Grodzinsky; Eliot H. Frank, PhD; Evan P. Salant, BS
Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA 02139; Harvard Medical School, Boston, MA 02138

Sponsor: *National Science Foundation*

Purpose—The long-term objective is to develop a nondestructive surface spectroscopic technique for early detection of degenerative joint disease, sensitive to molecular level changes in connective tissue that cannot be detected by current radiological or magnetic resonance methods. The immediate goals are to measure electrical and mechanical properties of cartilage on intact joints using electrodes placed on the articular surface. The ability to characterize the spatial and temporal behavior of electromechanical transduction in articular cartilage may enable detection of early stages of tissue degradation such as in osteoarthritis.

Progress—Recent theoretical studies suggest that a standing wave of electric current applied directly to the *articular surface* can result in a bulk mechanical stress, measurable at the surface. This *current-generated stress* is produced by the same electrokinetic mechanism as streaming potential. Here, we report: 1) measurement of this phenomenon in cartilage using a surface electrode geometry; 2) the relation between the measured stress and the amplitude and frequency of the applied current; and, 3) sensitivity of current-generated stress to changes in plasma glucose (PG) caused by chemical modification or enzymatic extraction.

Methods—Calf articular cartilage disks 800 μm thick and 7 mm diameter were harvested from the femoropatellar groove. The transducer is a 125 μm-thick laminated structure composed of piezoelectric film (Kynar PVDF Piezoelectric Film, Pennwalt Corp., Valley Forge, PA) and silver chloride stimulating electrodes. Each stimulating electrode is 1.5 mm $\times$ 4.0 mm with 1 mm separation. The metalization pattern on the piezoelectric film has the same geometry. The electrodes impose a spatial standing wave of current density resulting in a similar standing wave of mechanical stress. This stress is sensed by the piezoelectric film. The electrode separation (half spatial wavelength) allows penetration of current to be on the order of cartilage thickness; with thinner, more closely spaced electrodes, current would be confined to the superficial region. Independent mechanical calibration of the piezoelectric film as used in the transducer gave approximately 1 mV output per 1 kPa of applied stress.

Cartilage disks were held in unconfined compression at a constant offset stress of 50 kPa using a Dynastat spectrometer. The articular surface was held against the transducer and the other surface against a porous platen, so that one surface and the sides of the disk were in contact with a 0.05 M Na phosphate, 0.1 M NaCl buffer used previously in studies of trypsin digestion. A sinusoidal current density between ~0.25 and ~1 mA/cm^2, in the frequency range 0.025 to 0.5 Hz, was then applied to the cartilage via the transducer electrodes.

Results—The mechanical stress amplitude was measured as a function of applied current density and frequency for a series of normal cartilage specimens. The stress was observed to be proportional to current density and inversely proportional to frequency, consistent with the trends predicted by the poroelastic theory. In cartilage, the applied current causes electrophoretic displacement of the negatively charged PG/matrix toward the positive electrode, and an oppositely directed flow of positively charged interstitial fluid (electroosmosis). This combined motion generates the mechanical stress measured by the transducer. As the frequency is raised, these motions have less time to develop; the resulting stress amplitude is lower, consistent with experimental findings.

In another series of experiments, the mechanical stress was also measured as a function of buffer pH (adjusted by sequential addition of HCl after preequilibration at pH 8.5) for specimens subjected to 1 mA/cm^2 current density. The stress decreased dramatically at low pH. Decreasing pH in this region primarily neutralizes carboxyl groups of PG and collagen and, to some extent, may disaggregate PG aggregates rendering them more mobile. Both effects would decrease the electrokinetic coupling responsible for current generated stress, consistent with the trends of our data and previous streaming potential versus pH data. Addition of 1 mg/ml trypsin to the buffer at pH 7.2 led to a 78% decrease in stress amplitude by 5.5 hr; such trypsin treatment was found previously to extract 88-96% of the galactosamine and 75-91% of the glucosamine of adult bovine cartilage in 24 hr.

Implications—The pH and enzymatic extraction data suggest that surface measurement of current-generated stress may provide a sensitive means for detecting degradative changes or loss of FCD-determining matrix constituents. Theoretical analysis, supported by these data, suggests that a microfabricated, multiple-interdigitated electrode array could be used to vary the spatial wavelength as well as the frequency of the applied current; this may enable detection of focal changes at surface versus deeper zones of cartilage in intact joints.

Recent Publications Resulting from This Research

An Electromechanically Coupled Poroelastic Medium Driven by an Applied Electric Current: Surface Detection of Bulk Material Properties. Sachs JR, Grodzinsky AJ, Physicochem Hydrodyn 11:585-614, 1989.

[78] Measurement of the Degrees-of-Freedom of the Normal Human Knee In Vivo

Robert W. Mann, ScD; Michael C. Murphy, PhD
Newman Laboratory for Biomechanics and Human Rehabilitation, Mechanical Engineering Department, Massachusetts Institute of Technology, Cambridge, MA 02139

Sponsor: *National Science Foundation*

Purpose—Modelling is an essential tool for evaluating the dynamics and control of the human knee. A prerequisite to the development of a mathematical model of the knee is the complete characterization of the kinematics of the joint, in particular, the number of kinematic degrees-of-freedom. There is a dearth of detailed, confirmed lower extremity skeletal kinematic data reported in the literature. Much of the existing data are for only a single activity, level walking. Inadequate information about the motion of the knee under different movements and loads has led to the proposal of knee models ranging from a single-degree-of-freedom to 4-degrees-of-freedom. This specific investigation addresses the kinematics of the normal knee. The ultimate goal of this study is an experimental data-based, mathematical model of the human knee capable of characterizing normal and pathological performance, evaluating current internal prostheses and external orthoses, and recommending new designs for knee augmentation or replacement.

Methodology—As the initial step in an investigation of the control of the normal and pathological knee, a set of experiments to measure its kinematics for several different tasks was carried out with a single subject. Arrays of markers—infrared light emitting diodes (LEDs)—were mounted on skeletal pins and the TRACK kinematic data acquisition system used to measure the bone movements about the knee. Data were collected for activities including voluntary swing of the knee through its full range of motion, normal gait, and a pivoting motion common in athletics. Three-dimensional (3-D) marker coordinates were smoothed using the GCV-based algorithm of Dohrmann, and the rigid body orientation and position data were differentiated using a Lanczos filter to obtain velocities. The velocity data were then used to calculate the instantaneous helical axes (IHAs) of the different movements. The loci of the IHAs for a task define a pair of ruled surfaces, one in the fixed body, and one in the moving body. These surfaces are the axodes of the movement and are characteristic of the mechanism producing the motion. Fixed axodes for the different tasks were displayed on a Personal IRIS workstation.

Results—The results clearly show that normal knee motion is dependent upon the task being performed. The axode for the voluntary swing motion is that of a nearly planar movement with different trajectories for flexion and extension. Both normal gait and the pivoting maneuver are fully 3-D motions, each with a distinctly different sequence of IHAs. A joint or coupling such as the knee constrains the relative motion between two bodies. The allowable range of motions constitutes a screw system of an order equal to the number of degrees-of-freedom of the joint. The order of the system is determined by the number of independent screws in the system. Techniques are available for evaluating the independence of screws in a system, and for determining an orthogonal basis for a screw system. The number of active degrees-of-freedom for each of the different tasks was evaluated in both ways.

Future Plans—A second bone-pin experiment is in final stages of preparation. To complement the TRACK position-measuring system, a 3-axis accelerometer will be mounted on each TRACK LED array. Kinematic data will be processed both by smoothing and differentiating the position data, and integrating the accelerometer input with comparisons thereof. Data will be collected over a greater range of movements than the prior original bone-pin experiment and very specific protocols will be employed.

Recent Publications Resulting from This Research

Automatic 6-d.o.f. Kinematic Trajectory Acquisition and Analysis. Antonsson EK, Mann RW, J Dyn Syst Meas Control 111:31-39, 1989.

Geometry of the Kinematics of the Normal Human Knee. Murphy MC, PhD diss., Massachusetts Institute of Technology, 1990.

Instantaneous Helical Axes of the Normal Human Knee in Vivo. Murphy MC et al., East/West Coast Gait Laboratories Conference, San Diego, 1990.

Measurement of the Degrees of Freedom of the Normal Human Knee In Vivo. Murphy MC, Mann RW, in Proceedings of the Symposium on Dynamics and Control of Biomechanical Systems, 1990 ASME Winter Annual Meeting, Dallas, 1990.

[79] Using Axodes to Compare In Vivo Knee Kinematics Measured Using Bone versus Skin-Mounted Markers

Robert W. Mann, ScD; Michael C. Murphy, PhD; Jens O.M. Karlsson, MS
Newman Laboratory for Biomechanics and Human Rehabilitation, Mechanical Engineering Department, Massachusetts Institute of Technology, Cambridge, MA 02139

Sponsor: *National Science Foundation*

Purpose—Two problems inherent in biokinematic studies are: 1) whether skeletal motion is accurately measured by observing markers on the skin; and, 2) how to define body-fixed coordinate systems relative to skeletal segments. Typically, experimenters place markers on the skin over bony landmarks (i.e., locations where the skeletal members may be palpated through the covering soft tissue), with the implicit assumption that the marker motion is an accurate reflection of the underlying skeletal movement. Yet, several studies indicate that there are significant artifacts from soft tissue motion in kinematics measured with skin-mounted markers. However, quantitative information on the relative motion between the skin and bone is not available.

Progress/Methodology—A program of experiments was initiated to quantify any differences between the three-dimensional *in vivo* kinematics of the knee measured directly on the skeleton, and corresponding measurements using several different schemes for mounting markers on the skin. To compare the mounting methods, the same subject was used in all experiments, and the same tasks were performed. When comparing data from different experiments, consistency in the representation of the data is essential. Thus, kinematic representations such as Euler angles are not acceptable. Euler angles, as well as most other methods used in biokinematic studies, are dependent on how body-fixed coordinate frames are defined. Since the definitions of these coordinate systems with respect to the skeleton cannot be performed with consistency, a different type of representation must be used. By calculating instantaneous helical axes and studying the resulting axodes, assembled from these time-varying axes, a description independent of coordinate frame definitions was obtained.

The experimental data were collected using the Selspot optoelectronic motion measurement system, with infrared light emitting diodes (LEDs) used as markers, and the TRACK software. In the first experiment, the LEDs were mounted in groups of six on rigid, plexiglass arrays attached to skeletal pins placed directly in the tibia and femur of the subject. In subsequent experiments with the same subject, the arrays of markers were mounted on the subject using three different techniques: 1) taped directly to the skin over bony landmarks; 2) mounted on rigid, acrylic frames strapped to the subject's limbs; and, 3) mounted on molded, plastic forms held on the subject with a vascular stocking. Data were obtained for different tasks, including normal gait, and voluntary swing of the knee through its full range of motion.

Results—Results of the bone-mounted markers for a voluntary swing show a nearly planar motion with different flexion and extension trajectories. The taped-on markers gave the least accurate reflection of this pattern, while the third mounting scheme produced a good representation. For gait data, the directly measured kinematic data indicate a combination of planar motion and rotations about secondary axes. The skin-mounted markers showed a predominantly planar motion, and did not accurately measure out-of-plane rotation components. Discrepancies may be attributed to skin motion relative to the bone. Results thus far are for a single subject and need further confirmation.

Future Plans—A second bone-pin experiment will complement the existing database, and provide an opportunity to compare a wider range of skin-mounting methods for the marker arrays.

Recent Publications Resulting from This Research

Automatic 6-d.o.f. Kinematic Trajectory Acquisition and Analysis. Antonsson EK, Mann RW, J Dyn Syst Meas Control, 111(31-39):517, 1989.

Comparison and Analysis of Biokinematic Data Using Instantaneous Helical Axis Methods. Karlsson JOM, Masters thesis, Massachusetts Institute of Technology, 1990.

A Comparison of In Vivo Knee Kinematics Measured With Bone and Skin Mounted Markers. Murphy MC et al., East/West Coast Gait Laboratories Conference, San Diego, 1990.

Using Axodes to Compare In Vivo Knee Kinematics Measured with Bone and Skin Mounted Markers. Karlsson JOM, Murphy MC, Mann RW, in Proceedings of the Symposium on Dynamics and Control of Biomechanical Systems, 1990 ASME Winter Annual Meeting, Dallas, 1990.

[80] Dynamic Estimation of Joint Loading

Z. Ladin; G. Wu
NeuroMuscular Research Center, Boston, MA 02215

Sponsor: *Whitaker Foundation; National Science Foundation*

Purpose—The estimation of joint loads involves the calculation of joint forces required to generate a given movement. Hence, the knee-joint forces generated in the process of gait can be estimated by accurate measurements of the motion of the foot and the shank, and an estimate of the mass and inertial properties of these two segments. A general system for dynamic estimation of joint loads in multi-link systems is being developed. The system includes the WATRACK date-acquisition system in the Motion Analysis Laboratory, and kinematic transducers such as an angular rate sensor and a linear accelerometer, which are integrated into one unit for the determination of link kinematics. The kinematic measurements and estimates of the inertial properties of the link under study are used to calculate the joint loads required to generate a particular movement.

Progress—A well-controlled 2-degrees-of-freedom mechanical pendulum was constructed in order to evaluate this integrated kinematic measuring unit. The system was equipped with a series of strain gauges to directly record the joint loads. The measured joint loads were compared to the estimates based on both the WATRACK system alone, and the integrated kinematic measuring unit attached to the center of mass of the pendulum.

Results—The results show that the kinematic variables using the integrated kinematic measurement are the most accurate and, therefore, the most reliable basis for estimating joint loading. With the rapid development of advanced technology, the use of transducers (such as accelerometers and angular rate sensors), combined with displacement measurement to obtain the kinematic variables, presents an optimal and feasible solution for high-quality joint loads estimation.

Portions of this work were presented at the 13th Annual Meeting of the American Society of Biomechanics in Burlington, VT, in 1989. An abstract describing this work was published in the conference proceedings.

[81] Computer-Based Teaching Aid for Temporomandibular Joint Dysfunction

R.D. Bagnall; P.R. Geissler
The Dental School, University of Edinburgh, Old College, South Bridge, Edinburgh EH1 1NR Scotland UK

Sponsor: *None listed*

Purpose—The purpose of this study has been to develop a computer-based teaching aid to assist general practitioners in the diagnosis of temporomandibular joint dysfunction and its differentiation from other medical disorders which might resemble it. A diagnostic computer program for clinical use has been developed, and the current work has been based on a variant of this in which additional corrective text has been included to guide the user through any number of fictitious patients.

Progress/Methodology—A suitable CAL program has now been developed, and has been used in postgraduate courses to show qualified general practitioners how to approach the problem of temporomandibular joint dysfunction. The current program is not intended as a complete diagnosis-and-treatment, but rather has been designed to lead the clinician through all of the relevant questions that should be asked, and finally to indicate whether or not the patient should be referred to a specialist center for further investigation. A strong indication of joint dysfunction will result in a suggested referral. The user is first required to enter personal details of a fictitious patient, and the program then queries the presenting symptoms, medical history, and other symptoms such as stress, etc., until it is able to make a decision regarding referral. Users may invent any combination of symptoms subject only to constraints of self-consistency (e.g., the program will not allow the user to report pain in one part then deny it elsewhere). In the new teaching version of the program, the user is offered extra explanatory text should inconsistencies arise. A charting of the dentition is included, and the program will provide upon request both a hard copy of the data and a suitable referral letter.

The system has been written in Basic for a BBC microcomputer, but IBM versions are also available.

Preliminary Results—Questionnaires returned after postgraduate courses have shown that the CAL program has been well received and is regarded as a very useful teaching aid.

[82] Capture and Analysis of Joint Sounds

R.D. Bagnall; K.W. Tyson
The Dental School, University of Edinburgh, Old College, South Bridge, Edinburgh EH1 1NR Scotland UK

Sponsor: *None listed*

Purpose—The purpose of this study has been to develop a low-cost computer-based system for the capture of transient joint sounds, and to analyze these sounds for signs of disease or other joint malfunction. Concentrating initially on dental occlusion and the temporomandibular joint, and using a low-cost personal computer with suitable signal interface, a second purpose of the study has been to examine the feasibility of using a standard cassette tape recorder in the clinic, then replaying the recorded sounds into the computer for analysis at a later time, thus making the technique accessible to general practitioners in both medicine and dentistry.

Progress—A microcomputer-based system is now being assessed, and suitable software has been written to allow the capture of over 20,000 data points at a selectable sample rate in the approximate range of 1.5–67 KHz. The capture program is self-triggered once background levels have been assessed, and the signal envelope displayed on screen can be stretched or compressed by the software as desired. A plotter driver and built-in screen dump allow rapid production of hard copies of screen displays, and the captured signal can be saved to disc for later recall. Various problems with differences between tape-recorded and direct sounds are now being overcome, and attempts are currently in progress to include fast Fourier transform analysis in the software to shed light on the frequencies involved.

Methodology—The system being developed uses a BBC microcomputer to which is attached a Unilab interface (Unilab, UK). This low-cost interface is a general purpose signal input/output unit containing a fast analog-to-digital converter which allows rapid capture at a maximum sample rate of 125 KHz, although software restrictions in the current study reduce this figure by approximately a factor of 2. Signal detection is via an accelerometer (Knowles Electronics, UK) rather than a microphone because it can be placed directly against the joint without picking up ambient noise. The captured signal is either fed directly to the interface and/or recorder, or may be preamplified if desired. The software is fully menu-driven, and allows the user to set a signal level above background for the automatic triggering of capture. Up to 30 captured signals can be stored on a 5 1/4-inch diskette. Cassette tape recorders being investigated range from tabletop variable speed models to personal tape player/recorders.

Preliminary Results/Implications—The working system is already showing occlusal sound envelopes as detailed as those produced previously by conventional microphone/chart recorder techniques, and computer manipulation of the captured signal is revealing more detailed information. Multiple tooth contacts can easily be detected, and may be associated with either poor occlusion or temporomandibular joint problems. Preliminary studies of other joints, such as the knee, have produced unexpected sound envelopes even in apparently healthy joints, and it has even proved possible to record the human heartbeat. The results of fast Fourier transform analysis of the captured sounds are awaited with interest, since they might well show how much of each signal is joint-based, and how much is due to natural skeletal and soft tissue resonance.

[83] Anterolateral Instability of the Ankle

John P. Corrigan, MCh
Cappagh Orthopaedic Hospital, Finglas, Dublin 11, Ireland

Sponsor: *None listed*

Purpose—This study was initiated to investigate the conditions required to produce instability of the loaded ankle following section of the anterior talofibular ligament. It has been shown that rupture of the anterior talofibular ligament can lead to chronic lateral ligament instability of the ankle. Laxity of the joint can be demonstrated by an anterior drawer sign and talar tilt. These tests, however, are performed in tension, but the unstable ankle exhibits instability in compression and should be investigated as such.

Methodology—Cadaver ankles were mounted on a special jig in order to load the ankle in a vertical plane. The position of the heel could be altered to produce loading through the joint at any position from medial to lateral. The loaded joint was then cycled through a range of motion and the kinematics of the joint was studied.

Results—The instability demonstrated when the joint was tested in compression was anterolateral rotational instability. When the ankle was loaded on the lateral side of the joint, no instability was demonstrable until 100 nm external rotational torque was applied to the tibiofibular segment. However, with the joint loaded medially, spontaneous subluxation of the joint occurred.

Future Plans—Functional instability can be improved by proprioceptive rehabilitation of the peroneal muscle group which would be expected to apply an internal rotational torque to the tibiofibular segment and so reduce the tendency of the ankle to anterolateral rotational instability. It is proposed to investigate the contribution of this muscle group on the cadaver ankle subjected to compressive loading.

[84] Three-Dimensional Biomechanical Model of the Shoulder Mechanism

Gijs M. Pronk
Man Machine Systems Group, Laboratory for Measurement and Control, Faculty of Mechanical Engineering and Marine Technology, Delft University of Technology, 2628 CD Delft, The Netherlands

Sponsor: *None listed*

Purpose—The purpose of this project is to develop a three-dimensional (3-D) biomechanical model of the shoulder and shoulder girdle with which the effects of orthopedic treatment in the shoulder region can be predicted. The study has been focused on the prediction of the consequences of a glenohumeral arthrodesis of patients with an arm lamed due to a brachial plexus lesion.

Methodology—With the help of the computer program Spacar, based on a finite element approach, the shoulder mechanism can be modeled as a spatial mechanism consisting of beam, hinge, surface, truss, and slider truss elements which describe the properties of the bones, joints, thorax, ligaments, and muscles, respectively. For quantification and validation of the model, the following measurements were executed: 1) the 3-D positions of the scapula and clavicle were measured at several elevation angles of the humerus with and without loading the hand (30 subjects); 2) the 3-D humerus motions of 18 subjects with a glenohumeral arthrodesis were measured with the help of two video cameras; 3) a cadaver study in which the positions of the bones, the attachments of both ligaments and muscles, as well as the shape of all articular surfaces of 14 shoulder specimens, were measured three-dimensionally; and, 4) with 12 surface electrodes, the EMG-activity of 7 muscles was measured during humerus elevation with and without loading the arm (12 subjects).

Progress—An inverse dynamic model of the shoulder mechanism, including 16 muscles, 3 extracapsular ligaments, and the scapulothoracic gliding plane, is largely completed. Muscles are represented by a number of (straight or curved) lines of action. Several optimizing criteria are realized to estimate the muscle force. The 3-D motions of the shoulder mechanism are thoroughly analyzed. Axial rotation of the clavicle can be estimated by minimizing the rotations in the acromioclavicular joint.

The influence of the fusion position between the humerus and the scapula, as well as the role of the shoulder girdle muscles in positioning the hand after a glenohumeral arthrodesis, could be derived and analyzed by model simulations.

Future Plans—To get more insight into the cause of habitual subluxation of the glenohumeral joint, parts of the model will be used to investigate the control mechanism of the rotator cuff muscles by which the glenohumeral joint is stabilized. Further, the role of the muscles and ligaments will be analyzed by means of model simulations.

Recent Publications Resulting from This Research

An Adjustable External Fixator to Perform a Glenohumeral Arthrodesis. Nieuwenhuis FJM, Pronk GM, in Progress in Bioengineering, 170-173, J.P. Paul et al. (Eds.). Bristol: Adam Hilger, 1989.

The Consequences of a Glenohumeral Arthrodesis. Pronk GM, J Rehabil Sci 2(1):30-32, 1989.

A Kinematic Model of the Shoulder Girdle: A Resume. Pronk GM, J Med Eng Technol 13(1/2):119-123, 1989.

Modelling of the Shoulder Mechanism. Rozendal RH et al., in Proceedings of the 12th International Conference on Biomechanics, Los Angeles, 1989.

The Role of the Coracoclavicular Mechanism in the Motion Pattern Between the Scapula and Clavicle. Pronk GM, Van der Helm FCT, in Proceedings of the 12th International Conference on Biomechanics, Los Angeles, 1989.

B. Human Locomotion and Gait Training

[85] Development of a Sensory Substitution System for the Insensate Foot

Jacqueline J. Wertsch, MD; Gerald F. Harris, PhD, PE; Melvin B. Price, DPM, PT; Hongsheng Zhu, MS; Jay Loftsgaarden, BS
VA Medical Center, Milwaukee, WI 53295; Medical College of Wisconsin, Milwaukee, WI 53226; Marquette University, Milwaukee, WI 53233

Sponsor: *VA Rehabilitation Research and Development Service (Project #A383-DA)*

Purpose—Our goal was to develop a reliable, cost-effective, and portable insole pressure measurement prototype device.

Methodology/Preliminary Results—Our goal has been accomplished. Our system allows the long-term recording (up to 2 hours) of pressure-time data during ambulation for each step from 14 pressure sensors located within the insoles during various daily living activities. The recorded pressure data are then fed back to the subjects through electrotactile stimulation to assist their gait.

The insole data-acquisition system is portable, battery-supplied, and book-sized. The HD64180 microprocessor has the capacity of 512 kbyte physical memory. This system can collect pressure data from 14 channels at a 35 Hz sample frequency for 5 sec/min over a 2-hour period. It can also continuously collect pressure data for 15 min. A portable electrotactile stimulator for sensory feedback has also been developed. The stimulator has 14 inputs from the insole sensors and 14 corresponding electrodes on a belt worn around the waist for electrotactile stimulation. It can be used alone or in conjunction with our portable data-acquisition system for feeding back the processed information to the subjects. This sensory substitution device can also be used as a mobility aid for the blind subjects.

We have been conducting several clinical studies including sensate and diabetic insensate gaits, plantar pressures during shuffling and normal walking, assistive devices (canes and crutches), sensory substitution, and fatigued gait using the data-acquisition system. We have collected pressure data through the portable unit from 17 sensate and 4 insensate subjects for 4 minutes of continuous walking during multiple trials (60 sensate, 40 insensate), to explore sensate and insensate discriminators. Ten normal subjects have been studied for evaluating plantar pressure differences during shuffling and normal walking. The plantar pressures during ipsilateral and contralateral cane uses have been obtained from nine normal subjects as compared with normal walking. We are also examining data obtained during the fatigue gait of a 2-hour walk from eight normal subjects to find how normals vary pressure distribution pattern under the foot over time.

Future Plans—We plan to explore and identify those metrics that are significant discriminators between sensate and insensate gait. We will also evaluate the sensory substitution system as a blind mobility aide.

Recent Publications Resulting from This Research

Analysis of Foot Pressure Waveforms. Mehta D et al., in Proceedings of the IEEE Engineering in Medicine and Biology Society, 11:1487-1488, 1989.

A Capacitance Pressure Sensor Using a Phase-Locked Loop. Patel A et al., J Rehabil Res Dev 26(2):55-62, 1989.

Comparison of Interlink and Hercules Sensors for Plantar Pressure Measurement. Patel A et al., Arch Phys Med Rehabil 70-A:100, 1989.

A Conductive Polymer Pressure Sensor Array. Maalej N et al., in Proceedings of the IEEE Engineering in Medicine and Biology Society, 11:1116-1117, 1989.

Design of a Portable Electrotactile Stimulator for Use in Sensory Substitution Applications. Onesti RJ et al., in Proceedings of the IEEE Engineering in Medicine and Biology Society, 11:1439-1440, 1989.

Electronic Circuits for Capacitive Pressure Sensors. Patel A et al., in Proceedings of the IEEE Engineering in Medicine and Biology Society, 11:1437-1438, 1989.

Foot Pressure Distributions During Walking and Shuffling. Zhu H et al., Arch Phys Med Rehabil 70-A:15, 1989.

Locating High Pressures on Plantar Surface of the Foot. Zhu H et al., Arch Phys Med Rehabil 70-A:98, 1989.

Piezoelectric Sensor for Foot Pressure Measurement. Bhat S et al., in Proceedings of the IEEE Engineering in Medicine and Biology Society, 11:1135-1136, 1989.

Pressure Distribution Beneath Sensate and Insensate Feet. Zhu H et al., in Proceedings of the IEEE Engineering in Medicine and Biology Society, 11:822-823, 1989.

Sensory Substitution Systems for Insensate Feet. Wertsch JJ et al., Arch Phys Med Rehabil 70-A:48, 1989.

An Umbilical Data-Acquisition System for Measuring Pressures Between the Foot and Shoe. Zhu H et al., IEEE Trans Biomed Eng 37(9):908-911, 1990.

Asymmetry of Plantar Pressure During Normal Walking. Zhu H, Wertsch JJ, Harris GF, Arch Phys Med Rehabil (in press).

Foot Pressure Distribution During Walking and Shuffling. Zhu H et al., Arch Phys Med Rehabil (in press).
A Microprocessor-Based Data-Acquisition System for Measuring Plantar Pressures During Ambulatory Subjects. Zhu H et al., IEEE Trans Biomed Eng (in press).
Plantar Pressures with Contralateral Versus Ipsilateral Cane Usage. Wertsch JJ et al., Arch Phys Med Rehabil (in press).

[85a] Asymmetry of Plantar Pressures During Normal Walking

Jacqueline J. Wertsch, MD; Hongsheng Zhu, MS; Gerald F. Harris, PhD

Purpose—The purpose of this project is to study plantar pressure distribution during normal walking and analyze the asymmetry of plantar pressures between two feet.

Methodology—In-shoe plantar pressures were recorded from 10 normal subjects during 4 minutes of continuous walking to evaluate symmetry of right and left plantar pressures. A portable microprocessor-based data-acquisition system was used for data collection. All subjects (ages 23 to 40 years) walked on a 32 m walkway at a metronome-controlled cadence of 105 steps/min. Peak plantar pressures (average 142 steps per subject) under seven sensors of each foot were processed from the recorded pressure-time data and then summated for every step. An unpaired *t*-test with the p value of 0.05 was used to statistically evaluate the pressure differences between two feet.

Results—Of 10 normal subjects studied, five subjects showed significant differences ($p < 0.05$) between summated plantar pressures under right and left feet. Among them, three subjects had an average of 47% higher plantar pressures under the left foot than those under the right foot: two subjects had an average of 18% lower plantar pressures under the left foot than those under the right foot. Five subjects did not show significant differences ($p > 0.05$) between summated right and left plantar pressures. This study suggests that asymmetry of plantar pressures during walking can be seen even among normal subjects.

Recent Publications Resulting from This Research

Asymmetry of Plantar Pressures During Normal Walking. Zhu H, Wertsch JJ, Harris GF, Arch Phys Med Rehabil (in press).

[85b] Cadence Effects on Plantar Pressures

Jacqueline J. Wertsch, MD; Hongsheng Zhu, MS; Gerald F. Harris, PhD; Melvin B. Price, DPM, PT

Purpose—The purpose of this project is to evaluate the effects of different walking cadences on the in-shoe plantar pressures from normal subjects.

Methodology—We are using insoles, each instrumented with seven pressure sensors and a portable microprocessor-based data-acquisition system, for data collection. The sample frequency is 35 samples per second for each sensor. Seven sensors are located under the posterior heel, anterior heel, first metatarsal head, second metatarsal head, fourth metatarsal head, fifth metatarsal head, and the hallux. Ten normal subjects are chosen for our study. The height, weight, and leg length of each subject are documented. The subjects walk on a 32 m walkway at cadences of 60, 70, 80, 90, 100, 110, and 120 steps/min. All cadences are kept consistent with the use of a metronome. The *t*-test will be used to compare plantar pressures at different cadences.

Progress—This project is ongoing. To date, five normal subjects have been tested. Preliminary data indicate that there is an increase in plantar pressures as cadence increases. At low walking cadences, there is an unstableness during walking. Peak pressures, pressure-time integrals, and foot-to-floor contact durations at all selected cadences will be processed and analyzed. The effects of walking cadences on plantar pressures will be evaluated.

[85c] Normal Cane Cadence

Jacqueline J. Wertsch, MD; Robert Schulman, BS; Hongsheng Zhu, MS

Purpose—When studying plantar pressure it is recommended to control cadence because the velocity of walking (stride length × cadence) affects ground reaction forces. Cadence directly influences the anterior-posterior ground reaction force at toe-off, and has a major influence on the observed ground reaction forces in all three orthogonal directions. Thus, when studying the effect of a cane on plantar pressure it would be important to define the cadence studied. The literature, however, does not define what cadence would be appropriate to use for studies with a cane. The purpose of this study was to define the range of normal cane cadence.

Methodology—A standard J cane is being used. It is fitted to the distal crease of the wrist for each subject. We are using insoles each instrumented with seven pressure sensors and a portable microprocessor-based data-acquisition system for data collection. The sample frequency is 35 samples per second for each sensor. The system is completely battery powered; it is mounted within a 20cm × 18cm × 7cm metal box, and weighs 0.8kg. Subjects can carry the portable system in a backpack during ambulation. This system offers the advantages of portability and minimal interference with the subject's natural gait pattern. Timing data is available for every step for over 4 minutes of continuous recording time.

Results—This study is in progress. Ten normal subjects are being studied. Preliminary data shows approximately a 75% slowing in cadence with use of a J cane. Further work is in progress to define the cadence change with ipsilateral unloading versus contralateral unloading and various types of canes.

[85d] Long-Term Studies of Plantar Pressures Under Insensate Foot

Jacqueline J. Wertsch, MD; Hongsheng Zhu, MS; Gerald F. Harris, PhD; Melvin B. Price, DPM, PT; Jay D. Loftsgaarden, BS

Purpose—The objective of this research is to study the long-term variability of in-shoe plantar pressures.

Methodology—We are using insoles, each instrumented with seven pressure sensors and a portable microprocessor-based data-acquisition system, for data collection. Seven sensors are located under the posterior heel, anterior heel, first metatarsal head, second metatarsal head, fourth metatarsal head, fifth metatarsal head, and the hallux. Three diabetic subjects with insensate feet were included in our study. Their feet were free from ulcers, trauma, and deformities. Plantar pressures under seven locations were recorded during 4 minutes of continuous walking with a total of 41 tests (each consisting of six trials) over a 1-year period (total 11,500 steps). The subjects walked on a 32 m walkway at their free cadences (mean 105 steps/min) both with and without the assistance of a metronome, respectively. An unpaired *t*-test ($p=0.05$) was used for analyzing data consistencies and indicating statistical differences.

Results—The average intertrial consistencies of all tests were found to be 82% in terms of pressure-time integral, 85% in terms of foot-floor contact durations, and 74% in terms of peak plantar pressures. Pressure-time integral analysis showed inter-test consistencies in 50% of sensor sites. The other 50% showed significant inter-test differences: however, no specific pattern of changes was observed during the whole period. There were no significant differences in intertrial pressure consistencies between uncontrolled and controlled cadences.

Recent Publications Resulting from This Research

Pressure Distribution Beneath Sensate and Insensate Feet. Zhu H et al., in Proceedings of the Annual Conference of the IEEE Engineering in Medicine and Biology Society, 11:822-823, 1989.

[86] Assessment of Walking Handicap and Reflex Control of Normal and Pathological Walking

Mary Garrett, MSc, MCSP; Celine Meehan, MISCP; Saleem bin Shakoor, BSc, MISCP
School of Physiotherapy, University College Dublin, Dublin 7 Ireland

Sponsor: *Millenium Scholar: Department of Industry and Commerce, Dublin, Ireland; Mater Hospital College for Postgraduate Research, Dublin*

Purpose—The research activity in this Department is directed at human locomotion. There are two main strands: 1) assessment of walking handicap; and, 2) reflex control of normal and pathological walking.

Progress/Methodology—*Assessment of Walking Handicap.* The walking ability of 26 paraplegic patients was assessed by quantifying the patient responses to a questionnaire concerning their level of walking ability in the home and community. Correlational analysis revealed a good relationship between these scores, assignment to categories of functional walking ability by expert clinicians, and certain sections of the Sickness Impact Profile.

Results—The results support the use of six categories of functional walking ability developed by Dr. Jacquelin Perry and her group.

Future Plans/Implications—A scored questionnaire on walking ability in the home and community provides the initial database for a computerized system of assessment of walking handicap suitable as a means of communication of treatment outcome between the medical, rehabilitation, and social services currently being tested in the context of Eureka Project CALIES (i.e., Computer Assisted Locomotion by Implanted Electrostimulation).

Purpose—*Reflex Control of Normal and Pathological Walking.* Our purpose was to investigate changes in the excitability of the monosynaptic reflex during walking in the stroke patient.

Progress/Methodology—The excitability of the monosynaptic reflex was investigated in 10 stroke patients using the Hoffman reflex modified for use in walking. Previous studies demonstrated increased excitability of the monosynaptic pathway from the ankle extensor during stance phase, and decreased excitability during swing of walking in normal healthy man.

Results—The H reflex showed no significant changes in the excitability of the monosynaptic reflex during walking in the hemiplegic patient. This absence of modulation of monosynaptic reflex in the affected ankle extensor of stroke patients is likely to contribute to walking difficulty (e.g., facilitation of unwanted plantar flexion leading to toe stubbing).

Future Plans—We plan to investigate the relationship between impairment of reflex control and walking handicap in stroke patients, and to develop a computerized system of classification of walking handicap as part of a Telemedicine communications system.

Implications—This study will assist in the identification of the contribution of impairment of the monosynaptic reflex to walking handicap in stroke patient.

Recent Publications Resulting from This Research

Classification of Walking Handicap in Paraplegia. Meehan C, Garrett M, in Proceedings of the 5th European Regional Conference of Rehabilitation International, Dublin (in press).

Changes in the Excitability of the Hoffman Reflex During Walking in Hemiplegic Man. Garrett M, Bin Shakoor S, J Physiol, Proceedings of the Physiological Society, Belfast Meeting (in press).

[87] Comparison of the Kinematic and Kinetic Components of Gait in Adult Males with Obesity and in Males of Normal Weight

D. Bernhardt; Z. Ladin
Sargent College of Allied Health Professions, Department of Physical Therapy, Boston University, Boston, MA 02215; NeuroMuscular Research Center, Boston, MA 02215

Sponsor: *Foundation for Physical Therapy; Sargent College of Allied Health Professions; NeuroMuscular Research Center*

Purpose—The purpose of this study was to compare kinematic parameters at the knee and ankle, and the temporal and displacement factors in males of normal weight, with and without additional load, to those of males who were 40 to 70% overweight. Data were collected using the WATSMART optoelectronic position measurement system, and processed using the TRACK software. Small rigid arrays, instrumented with infrared light-emitting diodes, were attached to the thigh, shank, and foot of each subject. The position information measured by the cameras was then used to calculate the 6 degrees-of-freedom of each one of those links. The data were used to calculate the anatomic joint rotations involved in the process of gait. A voltage-differential system of foot-switches was used to correlate the joint rotations, and the kinematic events such as heel-strike, foot-flat, and toe-off.

Results—Results of the data analyzed for 5 normal-weight subjects, with and without load, and 5 obese subjects, suggest that a normal-weight loaded subject presents a different pattern of gait than an obese subject. The results of this study will be used to generate a normative biomechanical profile of gait for the overweight population.

A portion of this work was presented at the 64th Annual Meeting of the American Physical Therapy Association in Nashville, TN, in 1989.

[88] Quantification and Display of Musculoskeletal Anatomy

Robert W. Mann, ScD; Derek Rowell, PhD
Newman Laboratory for Biomechanics and Human Rehabilitation, Mechanical Engineering Department, Massachusetts Institute of Technology, Cambridge, MA 02139

Sponsor: *National Institute on Disability and Rehabilitation Research*

Purpose—Patient-specific anatomical data, in a form suitable for mathematical processing, are essential for accurate determination of the mass and inertial properties used in Newton's equation to calculate forces from accelerations (see "Mobility Analysis" project, p. 77), for specializing mathematically expressed, generalized musculoskeletal models to the particular patient's anatomy (see "Musculoskeletal Modelling" project, p. 79), and to provide the surgeon, via computer graphic displays, with realistic and accurate visual information describing the patient's anatomy (see "Computer-Aided Surgical Simulation of Femoral and Tibial Osteotomy" project, p. 59).

Progress—We have demonstrated the feasibility and practicability of applying computer tomography (CT) or magnetic resonance imaging (MRI) data to automatically calculate the mass, mass center, and inertial tensor of body segments with X-ray tomography. The CT number defines local tissue density and is converted to mass density for inertial properties and to grey scale to compute visualization displays. MRI image data requires contouring regions of different density (i.e., bone, muscle, etc.), and assigning tissue density values. We have developed software algorithms to automatically extract from CT and MRI data, and store efficiently in computer memory, the geometrical information necessary to generate colorgraphic computer displays of aspects of a patient's anatomy (i.e., the skeletal bones, joints, muscles, muscle insertions and origins, ligament insertions and origins, etc.)

Using such displays, we have demonstrated the ability to perform any conceivable intertrochanteric osteotomy using a three-dimensional (3-D) computer display of a patient's femur, described from actual CT data. Our approach is fundamentally different from that of commercial firms developing similar anatomical display capability (CEMAX, PIXAR, SIEMENS), in that we are interested in "doing surgery" on the display; that is, "cutting" bones and "glueing" them back together. Commercial firms are content to display the intact anatomy as is. Our approach makes very different demands on the organization and display of the database representing the anatomical information. For 3-D display and graphic manipulation of anatomical material, we are employing both the more common "pixel" approach (using a Silicon Graphics Personal IRIS 4D20) and a volumetric "voxel" method (on a Sun 4/280S system equipped with Sun/TRANCEPT image generator). The two methods are complementary. The surface representation method allows fast manipulation of the anatomy, but requires considerable preparation of the contours. The volumetric method requires little preprocessing, but is computationally expensive and requires specialized image processing hardware. The volumetric representation is clearly superior for computation of mass/inertial properties of patient-specific body segments. The volumetric displays are particularly striking graphically, and effective interactively. Starting with the external appearance of the body, software, using tissue density as control, can "strip off" the skin, then the subcutaneous tissue, followed by muscle, leaving the skeletal structure.

CT-based images of bone suggest higher densities at ligament and tendon insertion sites; thus, noninvasive patient-specific determination of this data for musculoskeletal modelling appears feasible.

Recent Publications Resulting from This Research

Automatic Three-Dimensional Mesh Generation of Skeletal Structures. Levesque S, Masters thesis, Massachusetts Institute of Technology, 1989.

Determination of Body Segment Parameters in Conjunction with Computer-Aided Surgical Simulation. Brown GA, Rowell D, Mann RW, East/West Coast Gait Laboratories Conference, San Diego, 1990.

[89] Mobility Analysis

Derek Rowell, PhD; Robert W. Mann, ScD
Newman Laboratory for Biomechanics and Human Rehabilitation, Mechanical Engineering Department, Massachusetts Institute of Technology, Cambridge, MA 02139

Sponsor: *National Institute on Disability and Rehabilitation Research*

Purpose—Quantitative functional assessment of neuromusculoskeletal disorders mandates an ability to acquire precise, accurate, and high data-sample-rates of the kinematics and dynamics of the affected person. Such measurement is imperative to confident evaluation of the individual's movement patterns before and after interventions such as surgery, physical therapy, and application of internal and external prostheses and orthoses. A major effort of the Harvard-MIT REC has been dedicated to what is now recognized as the premier movement analysis extant.

The MIT TRACK© (Telemetered Rapid Acquisition and Computation of Kinematics) software complements Selspot or other electro-optical or video cameras to process human movement data. The NEWTON program uses this kinematic data together with forceplate data and body-segment inertial properties to estimate the new forces and moments across the skeletal joints. Unlike other gait analysis systems which place markers on the skin over the putative joint "centers," TRACK is based on segmented analysis treating each body segment (i.e., foot, shank, thigh, pelvis), as a separate entity free to move in three-dimensional (3-D) space. Arrays of markers located on each segment permit acquiring, following, and recording the 6 degrees-of-freedom of each segment (3 translations and 3 rotations).

Other features of TRACK are:

- A normal and natural milieu for the human subject, minimizing artificial aspects of the experimental environment and the burden on the subject.
- High precision, 3-D kinematic data, with body-segment translations and rotations relative to a laboratory fixed frame of reference, at high data rates relative to the frequency components of human movement, in a form suitable for subsequent dynamic analyses.
- Automaticity—no human intervention in data acquisition and quantization to eliminate human subjectivity and error and to reduce drudgery.
- Real-time processing of kinematic and forceplate data to provide access to kinematic and dynamic results during or immediately after movement.

Progress—The TRACK system is operational at MIT and MGH, at Boston University's NeuroMuscular Center, and at the University of Bologna. Originally coded in FORTRAN and running under VMS on a DEC PDP

11/60, TRACK has been reprogrammed in the "C" language and transferred to a Sun 3 Microcomputer System running in UNIX. TRACK data are now available at over 100 Hz for real-time control of experiments requiring movement input. For observational and comparative purposes TRACK output is displayed as animated limb and body segments, each a four-color six-sided solid assembled into a representation of a person. This visual display, together with graphical information, is presented on a Silicon Graphics Personal IRIS (4D20) at 20 Hz. A version coded for personal computers is offered commercially by OsteoKinetics, Inc., Newton, MA, under copyright license from MIT.

The kinematic quality of TRACK output has inspired careful study of optimal postprocessing of the sampled position data to faithfully retain all movement—significant frequencies while producing trajectory smoothness essential to satisfactory differentiation. Velocity data are necessary for instant helical axis determination to present joint axis trajectories as axode in order to compare kinematic data independent of subject direction of movement and frame of reference. Acceleration data is necessary for dynamic estimates. Even higher order derivatives are necessary to apply differential geometry analyses to quantitatively compare axode trajectories.

Our study of optimal postprocessing has clearly demonstrated the advantage of smoothing over filtering. We have now compared position data acquired with TRACK arrays mounted noninvasively on the skin on body segments with comparable arrays mounted on bone pins into the skeleton *in vivo.* These, in turn, have been compared with the usual practice of other gait laboratories, that of mounting "joint center" markers on the skin over bony prominences at each of the lower extremities.

With fixed position cameras, the viewing volume for accurate data is about 2 m on the side, or one gait cycle. To study stride-by-stride variability and other noncyclical and wider ranging movement patterns, we have developed Large Volume TRACK. The fixed cameras now observe the subject via computer-controlled mirror systems which rotate to keep the light emitting diode (LED) array images aligned to the camera optical axes as the subject moves throughout a much larger viewing volume.

Advancing Large Volume TRACK required developing improved calibration means, both for correcting inherent nonlinearities in the camera lens and electro-optical transducers, and in relating the positions and orientations of the cameras to each other and to the laboratory frame. The internal camera calibration technique we have developed and demonstrated fully exploits the 12-bit digitization of the analog output of the lateral-effect diodes in the electro-optical cameras. The new external calibration system is clearly superior to both our prior technique of mounting the cameras on an optical bench and to the widely used Direct Linear Transform (DLT) space-frame approach. We use LEDs mounted on a simple planar frame, rotated about a vertical axis by a stepping-motor, so that the plane can first face one camera, sweep out a volume, and then be rotated to face the other. Eliminating the DLT space frame avoids difficult reflections from frame structure between an LED and the camera, yet rotation of the plane simulates a volume. Finally, a new calibration algorithm has been developed which does not require that both cameras simultaneously see the same LED.

Recent Publications Resulting from This Research

Automatic 6-D.O.F. Kinematic Trajectory Acquisition and Analysis. Antonsson EK, Mann RW, ASME J Dyn Syst Meas Control 111, 1989.

Biomechanical Analysis of Knee Motion Upon Stair Ascent and Descent. Markovich GD et al., in Proceedings of the 13th Annual Meeting of the American Society of Biomechanics, 116-117, Burlington, VT, 1989.

Human Analysis Movement—Opto-Electronics, LED Arrays, and Software Produce Rapid, Automatic, and Precise 3-D Position and Orientation Kinematics and Dynamics. Rowell D, Mann RW, SOMA 3(2), 1989.

Real-Time Analysis and Display of Kinematic Data. Lord PJ, Mann RW, East/West Coast Gait Laboratories Conference, San Diego, 1990.

Segmental Analysis in Kinesiological Measurements. Ladin Z et al., in Proceedings of the First World Congress of Biomechanics, La Jolla, CA, 1990.

A Technique for Large Volume Acquisition of Human Kinematics. Mansfield PK, Mann RW, East/West Coast Gait Laboratories Conference, San Diego, 1990.

Telemetered Rapid Acquisition and Computation of Kinematics: The M.I.T. TRACK Movement Analysis System. Mann RW, East/West Coast Gait Laboratories Conference, San Diego, 1990.

TRACK: The MIT Movement Analysis System Which Combines Opto-Electronics, LED Arrays, and Software to Produce Rapid, Automatic, and Precise 3-D Position and Orientation Kinematics and Dynamics. Rowell D, Mann RW, in Proceedings of the International Symposium on Gait Analysis State-of-the-Art of Measuring Systems and Their Importance in Prosthetic and Orthotic Technology, Berlin, 1990.

[90] Musculoskeletal Modelling

Robert W. Mann, ScD
Newman Laboratory for Biomechanics and Human Rehabilitation, Massachusetts Institute of Technology, Mechanical Engineering Department, Cambridge, MA 02139

Sponsor: *National Institute on Disability and Rehabilitation Research*

Purpose—Musculoskeletal modelling has been a focus in our research for over a decade. The accurate kinematics from TRACK and dynamic calculations using NEWTON make feasible the estimation of the time course and net force levels in each of the redundant set of participating muscles producing a movement pattern. However, to make such models subject-specific, the mathematically expressed models which define the three-dimensional geometry of the skeleton, joints, muscles, and ligaments of the human lower extremity must be adjusted to the parameters specific to the patient (i.e., bone length dimensions, and muscle/tendon origins and insertions). Our computer tomography and magnetic resonance imaging data approach produces the information necessary for such individualization of our musculoskeletal models (see "Quantification and Display of Musculoskeletal Anatomy," p. 76).

Progress—The data from the pressure-instrumented prostheses (see "Rehabilitation Implications of *In Vivo* Hip Pressure Measurements," pp. 291-294), and corroborating evidence from Newman Laboratory amputations prostheses research and the posture and balance studies at the Massachusetts General Hospital's Biomotion Laboratory have made increasingly clear the ubiquity and significance of agonist-antagonist muscle activity (co-contraction) in virtually all postural adjustments and movements. The significance of these findings to gait analysis, the estimation of joint forces and movements, muscular skeletal modelling, and individual muscle force determination using optimization approaches, cannot be underestimated. In a word, all extant studies of the above have been based on, or have yielded, the lower limit of the forces the muscles provide and the joints experience. Since all such studies start with movement data (i.e., kinematics), they reflect only the net muscle forces which cause the motion, due to the muscle moment at the joint. In co-contraction, muscles opposed (antagonistic) exert balanced forces and therefore, joint forces above these net values. But these balance forces do not contribute to the observed motion.

Results/Implications—Amputation prosthesis research in our laboratory is showing that co-contraction is essential to the control of the impedance or stiffness of the joint, especially when the human interacts with the environment, in the use of tools.

We are developing a new analysis technique to include co-contraction in our optimization analyses which estimates the force-time output of the individual muscles. In such studies, a cost or penalty function (e.g., energy expenditure), is minimized to find those solutions which also satisfy the dynamic constraint equations. Adding a new "stability" cost function requires that the muscle forces, and their aggregate, the joint forces, be adequate to keep the body stable during movement maneuvers.

Recent Publications Resulting from This Research

Agonist-Antagonist Muscle Co-Contraction: Ubiquitous but Unappreciated. Mann RW, in Proceedings of the 13th Annual RESNA Conference, Washington, DC, 57-58, 1990.

A 3-D In Vivo Knee Model: Relationships Between Geometry, Dynamics, and Kinematics. Fijan RS, Mann RW, ASME Winter Annual Meeting, Symposium on Issues in Modeling and Control of Biomechanical Systems, Dallas, 1990.

A Three-Dimensional Mathematical Model of the Human Knee Joint. Fijan RS, PhD diss., Massachusetts Institute of Technology, 1990.

[91] Development of a Gait Pathology Expert System

Jacquelin Perry, MD
Pathokinesiology Service, Rancho Los Amigos Medical Center, Downey, CA 90242

Sponsor: *National Institute of Arthritis and Musculoskeletal and Skin Diseases, National Institutes of Health*

Purpose—The goal of this project is to develop a knowledge-based (expert) system which identifies the cause of a patient's gait dysfunction from an analysis of basic gait data. The intent is to assist the clinician by providing the primary and secondary diagnosis, with an explanation of the underlying reasoning process.

Methodology—The approach involves: 1) design and development of an automated Data Analysis Expert System (DA/ES), or preprocessor, which will analyze and evaluate the raw data obtained from instruments and yield judgments relating the specific data set to the parameters of normal walking; 2) design the evaluation of a Gait Pathology Expert System (GP/ES), which uses the outputs from the DA/ES and a gait analysis knowledge base to identify the muscular dysfunction responsible for the observed deviations from normal gait; and, 3) making preliminary plans for establishment of a National Resource Center to disseminate results of this project.

Progress/Results—A system (DA/ES) to delineate automatically the timing and relative intensity of gait electromyographic (EMG) data has been designed and validated with normal and patient data. A normal database has been compiled consisting of EMG data (27 muscles), foot support pattern and gait phases information (104 subjects), and motion (50 subjects) analysis. Software modules defining deviations between the automatically delineated patient data and the normal data bank have been developed. The basic GP/ES has been completed and validated with patient data for ankle gait deviations. "Reference frames" store the knowledge base. A rule-based tree structure has replaced direct matching of patient frames. The causes of five gait deviations have been related to seven modes of muscle action and foot switch patterns with hip and knee compensating postures included.

Future Plans/Implications—Proposed are means of improving DA/ES sensitivity to pathology. Normal phasing of the two joint muscles will be refined with new data which relate variations in EMG to their other functions. The phasic changes in EMG intensity during a muscle's activity period will be defined. For use of the DA/ES with surface EMG, the effects of different filters and the ability to differentiate the actions of the 21 muscles with surface exposure will be determined. The diagnostic capability of the GP/ES will be extended by incorporating a qualitative physiological mode (QPM).

This will be used when the tree/frame system does not provide a diagnosis. Efficiency of the QPM will be enhanced by an inductive learning module which extracts rules from repeated solutions. Means of handling variability will be developed and inferences will be added to the clinical explanation. Validation with patient records will be ongoing. Outcome will be judged by two external gait experts. An instructional course and commercial availability will disseminate the information.

Recent Publications Resulting from This Research

The Sequence of Extensor Muscle Control in Walking. Perry J, Gronley JK, Bontrager EL, in Proceedings of the 36th Annual Meeting of the Orthotics Research Society, New Orleans, 1990.
Computer-Aided EMG Analysis of Gait. Bontrager EL, et al., in Proceedings of the First World Congress on Biomechanics, San Diego, 1990.

[92] Curve Estimation in Motion Analysis

E.N. Biden
Institute of Biomedical Engineering, University of New Brunswick, Fredericton, NB E3B 5A3 Canada

Sponsor: *National Science Foundation*

Purpose—Our primary interest in this project is to develop methods to describe gait data in such a way that it can be used for clinical decision-making, and to expand a course of work in which nonparametric smoothing and the bootstrap are applied to several real-world problems in biomechanics and robotics. This involves developing methods to detect and classify abnormalities.

Progress—This project has advanced in several areas. Much of the work of the past year has been data checking on the gait data for the analyses. This has been completed and errors corrected. Two projects, in modeling how output errors propagate from errors in the input, and work on measuring dynamic robot motion, have advanced. Similar work in the area of robotics may allow for better control strategies or diagnosis of controller problems.

Recent Publications Resulting from This Research

Sensitivity of Cruciate Force to Input Data Error. McGibbon C, Biden E, Sexsmith J, Fifth Annual East Coast Clinical Gait Laboratories Meeting, 1989.
How Many Subjects Do You Need to Define Normal. Biden E, First Combined East/West Coast Gait Laboratories Conference, 1990.

[93] Assessment of Variability in Human Walking and in Robots

E.N. Biden
Institute of Biomedical Engineering, University of New Brunswick, Fredericton, NB E3B 5A3 Canada

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

Purpose—The purpose of this project is to expand on existing variability models which are applied to human movement for gait analysis, and to extend the analysis to robot motion.

Progress—During the past year the effects of sample size on the ability to define "normal," and the effect of side-to-side phase shifts have been examined and reported.

Recent Publications Resulting from This Research

A Comparison of Two Classification Methods for Gait Data. Biden E, Kelly M, in Transactions of the Canadian Orthopaedic Research Society, 1989.
Sensitivity of Cruciate Force to Input Data Error. McGibbon C, Biden E, Sexsmith J, Fifth Annual East Coast Clinical Gait Laboratories Meeting, 1989.
Side to Side Symmetry in Knee Flexion. Biden E, Wyatt M, Sutherland D, Fifth Annual East Coast Clinical Gait Laboratories Meeting, 1989.
Side to Side Symmetry in Normal Knee Flexion. Biden E, Wyatt M, Sutherland D, presented at the Combined Meeting of The Canadian Ortho Research Society and Canadian Orthopaedic Association, 1990.
Transverse Acceleration, Velocity and Displacement in Robots in Straight Line Motion. Boudreau R, Biden E, presented at the 9th Canadian CIM/D, Toronto, 1990.

[94] Clinical Assessment of Hemiplegic Gait Following Stroke: A Pilot Study

Frank Bell, BSc, PhD, CEng, MIMechE, MBES; Karen Hughes, BSc, MCSP
The Queen's College, Glasgow G3 6LP Scotland

Sponsor: *Scottish Home and Health Department*

Purpose—Our purpose was to develop and pilot-test a gait assessment form for recording the visual observations of clinicians on patients with hemiplegic gait following stroke.

Methodology—A detailed gait analysis form is being developed in conjunction with physiotherapists at The Queen's College, Glasgow, and various Glasgow hospitals. Concurrently, stroke patients are being filmed walking along an instrumented walkway. Six patients will be filmed at two stages in their recovery, using antero-posterior and lateral cameras mixed to give a split-screen film. These films will then be watched by three experienced stroke rehabilitation physiotherapists, who will use the form to rate the patients' gait. Validity of the form will be tested by comparing the completed forms to the walkway data, which gives information on speed and symmetry (in particular, speed, single-support symmetry, and step-length symmetry, although other parameters available from the walkway will be used in the final analysis if necessary). Reliability of the form will be tested by having the same rater score the same video on three different occasions (intra-rater reliability), and by having different raters score the same video (inter-rater reliability). Correlations will be examined between the subjective and the objective data.

Progress—The instrumented walkway and cameras have been set up in the Rehabilitation Department at the Southern General Hospital, Glasgow. Five patients have been filmed at various stages in their recovery, but it has been found that some of the data collection sessions will have to be discarded as the patients' gait was too poor to allow the walkway to collect valid data. It has also been noted that there tends to be a learning effect on the patients as they get used to the unfamiliar walkway. The first trial for any patient is, therefore, discarded, and the data collection proper starts on the second trial which is held the day after the first trial, where possible.

We will be starting the rater trials shortly as the form is in the final stages of development, and enough patient videos have been collected to make up suitable tapes.

Results/Implications—So far, the results are confined to the walkway data. These appear to confirm the usefulness of speed and symmetry as measures of recovery, and the walkway has proven to be sensitive enough to record very minor changes in gait. In particular, it has shown that as patients improve, not only do their speed and symmetry improve, but the variability of these parameters as measured by the standard deviation decreases (i.e., they become more consistent). However, this observation will have to be confirmed in a later study.

[95] Mechanics of Ankle-Foot Orthoses

Narender P. Reddy, PhD; Tai-Ming Chu, MS; Paul C. Lam, PhD; Mark Yanke, CO
Departments of Biomedical Engineering and Mechanical Engineering, University of Akron, Akron, OH 44325;
Yanke Bionics, Inc., Akron, OH 44325

Sponsor: *University of Akron*

Purpose—Excess rotations at the ankle-foot complex present a major problem in the comprehensive rehabilitation of certain stroke patients with upper and lower motor lesions. These patients have uncontrolled muscle activity which may develop into the "drop-foot" problem. Abnormal rotations also occur in the case of certain ligament injuries. Ankle-foot orthoses are generally prescribed to mitigate this problem. However, these orthoses have not been evaluated from a biomechanical viewpoint. The purpose of the present investigation is to study the biomechanics of ankle-foot orthoses.

Progress—We have developed two-dimensional finite element models of the ankle-foot-orthosis complex and studied various static and dynamic loading conditions. We compared stress and deformation patterns of the normal foot with those fitted with an orthosis.

In addition, we experimentally examined the strains developed in the orthosis in a walking cycle. Strain gauges were attached to polypropylene orthoses. The orthoses were fitted to normal test subjects and the strains were recorded during the gait cycle. The orthosis was held in place with a strap anterior to the calf and a shoe which held the foot in the lower section. Principal strains were determined from three element Rosett gauges with assumed values for the material properties.

Preliminary Results—Peak stresses determined from both static and dynamic finite element models were similar in magnitude. Experimental results with strain gauges were consistent with the results of finite element model simulation. Slight geometric modifications of the orthosis were made to eliminate stresses at undesirable points. These design modifications allow functional plantar flexion, reduce instability at the subtalar joint, and facilitate heel-to-toe gait pattern.

Future Plans/Implications—While the present simple two-dimensional analyses demonstrate the feasibility of using finite element models for redesigning the ankle-foot orthoses, further examination of dynamic conditions and more complex three-dimensional (3-D) dynamic finite element calculations are needed to be able to predict the total response of the ankle-foot orthosis system.

We are developing 3-D finite element models of ankle-foot-orthosis systems. In addition, we propose to test-fit the orthoses to human subjects and examine the effect of these orthoses on knee, ankle, and subtalar joints. Also, we plan to verify the results of the 3-D finite element model with experimental stress analysis of these orthoses. This would provide a comprehensive biomechanical understanding of the ankle-foot-orthosis systems.

[96] Development of a Posture Sensor and Evaluation System for Use in Gait Training of the Locomotion Disabled

Hiroyuki Miyamoto, Dr-Ing
Department of Computer Science, Chiba Institute of Technology, Chiba 275 Japan

Sponsor: *None listed*

Purpose—In the locomotion-disabled person, such as paraplegic or hemiplegic patients with balance deficits, information about pelvic inclination is most useful from the rehabilitation point of view. In the present study, pelvic inclination and its time derivative in the sagittal and frontal plane, as well as in the transversal plane during walking, are measured by the use of an inclinometer based on the gyroscope principle. This posture sensor system is used to evaluate gait and its improvement, if any, through rehabilitation.

Methodology—Inclinometer and angular rate sensors are put on the pelvis by belts for measurement of absolute angular displacement of the pelvis in sagittal and frontal planes, and measurement of angular rate in the transversal plane, respectively. Foot-switch sensors on the soles of the patient's shoes are used to detect plantar contact instants. The information is acquired and treated on-line in real-time by a 16-bit personal microcomputer via A/D converter.

Progress—Several software programs have been developed for measurement, data processing, and graphic presentation on-screen, and then tested on the normal subjects' walks as well as on patients having hip-joint disorders. Some criteria softwares have been developed to evaluate rehabilitation exercise.

Preliminary Results—Preliminary experiments indicate that a graphic presentation shows basic characteristics of each patient's gait: for example, the walk of women who have osteoarthritis at the hip joint before and after surgical operation. Data acquired from normal subjects and patients have been characterized by the proposed check points with regard to the waveform. It has been shown that these points can reveal the differences between them. Six features of a set of angular patterns were pointed out, and some were found to be invariant, while the rest vary, reflecting the degree of the disorder. Preliminary experimental results show the effectiveness of this system in the quantitative gait analysis, and evaluation of the patient's progress in rehabilitation exercise.

Future Plans/Implications—We expect to develop an expert system of analysis and evaluation of gait of each patient for use in a rehabilitation program, and for evaluation of its effects. This system is simple, compact, and especially suitable for clinical applications.

Recent Publications Resulting from This Research

Development of Measuring and Evaluating System of Three-Dimensional Angular Displacement of Pelvis During Walking. Miyamoto H, Yamazaki T, Kitame S, Ishida T, in Proceedings of the 11th Biomechanism Conference (SOBIM Japan), 153-156, 1990 (in Japanese).

C. Other

[97] Nuclear Magnetic Resonance (NMR), Biochemical, and Biomechanical Studies of the Human Foot Pad

William G. Winter, MD
VA Medical Center, Denver, CO 80220

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Purpose—Our preliminary studies with human foot pads indicate that the human foot pad tissue consists mostly of triglycerides and that their component fatty acids are more unsaturated than those of other adipose tissue triglycerides found in the body. Increased unsaturation results in a decreased viscosity of the triglycerides.

Biomechanical formulation predicts that decreased viscosity improves the shock absorption properties of the foot pads.

Our research goals are to: 1) develop a noninvasive method permitting the quantitation of the amount of lipid in the human heel pad; 2) develop an apparatus to test the biomechanical properties of the human heel pad *in vivo* in an attempt to correlate the composition data with biomechanical properties; and, 3) continue the biochemical studies on the composition of the fibro-fatty tissues of "normal" and abnormal human foot pads obtained at surgery. It is hoped that this information will lead to prevention of some human foot disease and improved treatment of such disease.

Results—The continued biochemical studies on "normal" human foot pads have confirmed in 60 human foot pads that our preliminary observations on the unsaturation of the fatty acids were correct and have provided us with statistically significant results. We are now collecting foot pads from abnormal conditions. All the nonlipid residues obtained from the foot pads have been saved and preliminary evidence (hydroxyproline analyses) indicate that most of this residue is collagen. We are currently setting up a procedure that will allow us to type these collagens.

The procedures to quantitate the amount of lipid in the human heel pad by determining lipid-to-water ratios by nuclear magnetic resonance (NMR) have been improved, which will facilitate the examination of additional patients by this noninvasive procedure. The diabetic females examined (n=4) had a significantly lower lipid-to-water ratio than normal females (n=12) at the P=0.01 level. However, the differences between normal and diabetic males were not significant. These studies will be expanded in order to improve the statistical significance and to examine the surprising differences between sexes since it is now commonly believed that no sex difference exists in diabetes mellitus.

The apparatus for noninvasively evaluating the viscoelastic properties of *in vivo* human heel pads is operative. All the software problems have been resolved and we are currently optimizing all parameters on volunteers' and cadaver heel pads. We expect to examine the same subjects on the same day by using NMR to obtain the lipid-to-water ratio, and using the viscoelastic properties of the heel pads with this device, to determine if a correlation exists between these two parameters. Of special interest will be the determination of the viscoelastic properties of the heel pads of those diabetic females that have low lipid-to-water ratios as determined by NMR.

Future Plans—Apparatus and procedures for measuring the mechanical properties of human heel pads *in vitro* and *in vivo* are now complete. We plan to investigate mechanical heel pad parameters, including viscoelasticity, to compare them to NMR properties concurrently, and to biomechanical parameters as established for similar cases of individuals during the earlier part of the study.

[98] An Investigation of the Relationship of Postural Sway and Endurance in Sitting

Wallace Lotto, MD, FRCS(C), FACS; Morris Milner, PhD, PEng, CCE; Denise Reid, PhD, OT(C); Ruth Koheil, DipP&OT, BSc(PT); Alex Sochaniwskyj, BSc, BASc; Kazek Bablich, MSc, RPT
The Hugh MacMillan Rehabilitation Centre, Toronto, Ontario, M4G 1R8 Canada

Sponsor: *Easter Seal Research Institute of Ontario*

Purpose—This study focused upon the evaluation of postural sway in sitting of 50 normal and 16 neurologically impaired children. A postural tracking system was used to monitor stability (trunk sway) during static sitting on a conventional horizontal seat base, and to determine the effects of a forward-inclined seat base on sway of children with cerebral palsy, and children with traumatic head injury. The objectives of this study were twofold: 1) to examine the developmental nature of sway in static sitting balance of normal children, so that these data could be used as benchmarks for evaluating sway in disabled children; and, 2) to examine the effects of horizontal (0 degree) and forwardly-inclined (10 degree) seats on stability of neurologically impaired children.

Methodology/Results—Sitting stability was defined as the standard deviation of trunk movement along three axes. A significant linear trend between sitting stability and age in normal children was observed. Sitting stability was poorer in children with cerebral palsy than in normal children, while no difference was observed between the normal and head-injured children. When the seat angle was tilted 10 degrees anteriorly, there was no difference in trunk sway for either group.

[99] Biomechanical Measurements for Quantitative Assessment and Diagnosis of Dysphagia

Narender P. Reddy, PhD; Enrique P. Canilang, MD; Judy Casterline, MA, CCC-SP; Sujat Sukthankar, BE; Rony Thomas, BE; Susan Gough, MA
Department of Biomedical Engineering, University of Akron, Akron, OH 44325; Rehabilitation Engineering Research Laboratory, Edwin Shaw Hospital, Akron, OH 44312

Sponsor: *Edwin Shaw Hospital Foundation*

Purpose—Dysphagia is a swallowing disorder resulting from neurological impairment. It presents a major problem in the comprehensive rehabilitation of patients with stroke and other head injuries. Further, dysphagia often leads to several clinical problems such as aspiration, dehydration, and inadequate nutrition. Identification of the patient at-risk of aspiration is important from a clinical standpoint.

The swallowing process can be divided into three distinctive phases: oral, pharyngeal, and esophageal phase. We are developing procedures for quantitative assessment and diagnosis of dysphagia involving the oral and pharyngeal phases.

Progress/Methodology—We have identified and developed techniques to measure several biomechanical parameters which aid in the quantitative assessment of the oral musculature in dysphagia. These parameters include: 1) lip closure pressure; 2) lip interface shear force; 3) tongue thrust in forward, backward, and two lateral directions; and, 4) swallow pressure.

For the quantification of the pharyngeal phase, two ultra-miniature accelerometers were placed on the outside of the throat. In addition, the swallow pressure was monitored with a catheter placed at the base of the tongue and connected to a pressure transducer. Normal subjects and dysphagic patients were measured for acceleration and swallow pressure simultaneously. A correlation was also made between the biomechanical measurements and videofluorography examination.

Preliminary Results—We found statistically significant differences in the above parameters measured in normal and dysphagia patients. In current clinical practice, the strength of the oral musculature is assessed using tongue depressors and lollipops. The biomechanical parameters devised in the present investigation can aid the physician to objectively assess the recovery of the dysphagic patient.

Swallowing in normal individuals gave rise to a characteristic acceleration pattern which could be well-reproduced. The amplitude of acceleration varied from 1 to 2 g. There was no time lag between the appearance of the pressure wave and the appearance of the acceleration wave characteristic of swallowing.

By contrast, in 35 dysphagic patients, the characteristic acceleration pattern was either absent or significantly delayed. The amplitude of acceleration varied from 0 to 0.5 g. In those patients who could trigger a swallow, we found significant lag times between the acceleration and pressure waveforms. Additionally, we measured the biomechanical parameters in several patients upon admission, and after 3 weeks of thermal exercise therapy. We found significant improvements in the acceleration amplitude and pattern after the 3-week therapy. We found similar improvements in oral biomechanical parameters (tongue thrust, lip pressure, etc.), after 3 weeks of oromotor exercises.

We have made biomechanical measurements (BM) of the oral and pharangeal phases within 7 days of videofluorography examination (VFE) in 36 patients. Both results were independently classified into three categories of risk for aspiration. In 21 cases, there was a complete agreement between BM and VFE. In 11 cases, the BM overestimated the risk by one category, and in 4 cases, underestimated the risk by one category. Wilcoxon, and paired *t*-test did not indicate statistical difference between the two methods.

Future Plans/Implications—The biomechanical parameters identified and the measurement techniques developed in this study can be used for quantitative evaluation of the patient and for patient training to speed up the recovery process. Acceleration, when measured simultaneously with the swallow pressure measurement gives a quantitative picture of the coordination of the swallowing mechanism and can be used in the diagnosis of dysphagia.

In current rehabilitation practice, the pharyngeal phase and coordination are assessed using videofluoroscopy (radiography) which is often very expensive. Our results on the dysphagia patients correlated well with the VFE. However, a study on a large number of patients is necessary.

We are currently in the process of developing and testing instrumentation for biofeedback training for oral dysphagia by giving a visual feedback of the biomechanical measurements. Our hypothesis is that the biofeedback will accelerate the recovery process. Also, the acceleration patterns have to be evaluated in the frequency domain to identify the critical frequencies.

Recent Publications Resulting from This Research

Biomechanical Measurements to Characterize the Oral Phase of Dysphagia Patient. Reddy NP et al., IEEE Trans Biomed Eng 37:392-397, 1990.

Clinical Correlation of the Biomechanical Measurements of the Dysphagic Patient. Canilang EP et al., American Congress of Rehabilitation Medicine Conference, Phoenix, AZ, 1990.