1st Annual Meeting

American Society of Biomechanics

ABSTRACTS

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FAILURE CHARACTERISTICS OF HUMAN BONE

Albert H. Burstein (The Hospital for Special Surgery, New York)

One of the most common diseases in our society is bone fracture. In order to understand the cause and properly treat this condition, fundamental understanding of the failure properties of bone is required.

In this presentation, failure modes for bone tissue under tensile, compressive and shear loadings will be discussed. Changes in failure characteristics that arise as a consequence of the normal aging process will be described.

Particular attention will be given to the differences between juvenile and adult bone, and between young and aged bone. Some of the currently proposed composite models of bone tissue will be described. Application of these concepts to whole bone fracture will be presented and finally the bio-dynamic nature of bone will be discussed with emphasis on fatigue-type failures.

THE COMPRESSIVE BEHAVIOR OF TRABECULAR BONE

Dennis R. Carter (University of Washington) and Wilson C. Hayes (University of Pennsylvania)

Compression tests of human and bovine trabecular bone were conducted over a wide range of strain rates. By analyzing the results in light of the mechanical behavior of compact bone, we established fundamental relations between bone apparent density and compressive strength modulus, and the applied strain rate. Twenty-four cylindrical bovine specimens and 100 specimens of human bone were machined under continuous irrigation. Specimens were 5 mm thick and 10.3 mm in radius. They were removed from human tibial plateaus and bovine femoral condyles and were oriented with their axes parallel to the long axis of the bone. Half of the human specimens and all the bovine specimens were tested after the marrow had been removed with an air jet and running water. The specimens were tested in uniaxial strain by confining them in a rigid cylindrical cavity. Porous platens allowed for the escape of marrow during testing.

Viscous flow of marrow led to strengthening and stiffening of bone only in the ten specimens tested with marrow at the highest strain rate ($\dot{\varepsilon} = 10\ sec^{-1}$). For all other specimens, the strain rate effect on the modulus and strength was similar to that previously reported for compact bone. The results suggest that both the compressive strength and modulus of all bone tissue are approximately proportional to the strain rate raised to the 0.06 power. The compressive strength was approximately proportional to the square of the apparent density, and the compressive modulus was proportional to the cube of the apparent density.

STRESSES IN THE WALLS OF AN OSTEONAL REMODELLING CAVITY AND THEIR POSSIBLE PHYSIOLOGIC SIGNIFICANCE

R. Bruce Martin and James H. Morris (West Virginia University)

Using a two-dimensional aluminum model, the stresses on and near the walls of a hole shaped like an osteonal remodelling cavity were determined using strain gauges. These measurements confirmed the existence of tensile stresses on the formation surface, and demonstrated that the stress concentration factors at the cavity wall can exceed 2. Using a previously described theory, the predicted physiologic consequences of these variations in stress are seen to be concert with a variety of histologic observations, including (a) the distribution of cells in the cavity; (b) the tendency of osteons to align themselves with the principal compressive stress direction; (c) the greater bone formation rates near the front of the filling cone; and (d) the tendency of compact bone to become osteoporotic when stresses are reduced, and vice versa.

BIOMECHANICS OF SPORT RESEARCH: WHAT SHOULD THE FUTURE HOLD?

Doris I. Miller (University of Washington)

Although researchers in the biomechanics of sport are making encouraging progress in contributing to the understanding of the mechanics of human motion, four areas come to mind in which gaps need to be bridged or existing ties strengthened. These include closer communication with individuals and groups in other application areas of biomechanics and further cooperative research with colleagues in the exercise sciences. In addition, since the domain of biomechanics encompasses the biological substrate at one extreme and mathematical models at the other, a critical review of how these extremes are being and can be assimilated effectively into the study of sport is in order. And finally, more investigators should be encouraged to carry their research beyond temporal relationships and total body center of gravity analyses to a careful consideration of the role of the individual segments in producing the coordinated motor patterns which characterize skilled performance.

PREDICTION OF DISTAL EXTREMITY MOTION FOLLOWING RELAXATION OF KNEE MUSCLE FORCES

Sally J. Phillips, Elizabeth M. Roberts and T.C. Huang (University of Wisconsin-Madison)

A mathematical model was developed to study the resulting motion of a distal segment when the muscular force at the knee was relaxed. Of interest in this study was the mechanism of knee extension during the swing phase of kicking when maximum foot speed was the primary objective. The resulting muscular forces and moments of muscular force acting at both the hip and knee joint were initially calculated from cinematographical analysis with smoothing accomplished by cubic spline functions. Equations of motion for a system of two linked rigid bodies modeling the thigh and leg were then applied to predict the motion of the leg after the muscular force and moment acting about the knee joint were set to zero. The behavior of the new system now depends only upon the kinematics of the hip joint and the muscular force and moment of muscular force acting at the hip joint. Various time points at which the knee muscular force was relaxed during the swing phase of the kick were studied. The resulting leg motion at various succeeding time points was compared to the motion observed when the knee muscular force and torque were operant. Details of the results are reported.

THE USE OF ORTHOTIC DEVICES TO MODIFY FOOT MECHANICS *

B.T. Bates, S.L. James and L.R. Osternig (University of Oregon)

Excessive foot pronation has been speculated to be a cause of leg and foot problems among runners. Orthotic prescriptions are often used to counter this condition. Examination of the records of 180 patients treated for various running injuries showed that 83 individuals (46%) were prescribed orthotic treatment and that 65 of these runners (78%) were able to return to greatly reduced or pain-free running. In order to further assess the effects of orthotic devices, 5 runners were selected for additional study. These subjects were filmed while running on the treadmill using two high speed, super 8 mm cameras operating at 200 fps. Films were obtained of foot placement from the rear, and lower limb movement from a lateral view. Subjects were filmed under 3 conditions: (1) barefoot, (2) regular shoe, and (3) regular shoe plus orthotic device. The film was evaluated using a stop-action projector in conjunction with a digitizer interfaced to a Tektronix 4051 Graphic System. All raw data were treated with a cubic spline data fitting program prior to computation of final values. The results for conditions 1 and 2 showed pronation beginning significantly sooner and ending significantly later when compared to a group of injury-free runners. Condition 3, however, resulted in a modification of the temporal sequence resulting in a similar pattern to that produced by the injury-free runners. Values in maximum pronation were significantly reduced between conditions 1 and 2 compared with condition 3 with final results being similar to the injury-free runners. In summary, the data support the conclusion that orthotic devices can be used to successfully modify foot and leg function, during the support phase of running.

* Supported by a grant from the Northwest Area Foundation, St. Paul, Minnesota

BIOMECHANICAL INTERPRETATION IN FUNCTIONAL MORPHOLOGY

Carl Gans (University of Michigan)

Functional morphology uses a combination of observation and experiment to examine the matching of animal structures to the adaptive requirements of their particular environmental niches. Its questions consequently derive from the view that structures may participate in carrying out multiple comparable and sometimes conflicting biological roles. Consequently, it is often impossible to extrapolate the major functions performed by a particular element from a purely structural analysis. Indeed the functions that are actually performed by a structure may only be established by observation or measurement. The intrinsic complexity of animal systems furthermore requires that the approaches had best proceed by successive approximations. The resulting measurements provide one input for biomechanical analysis that may establish how closely the actual structure is matched to the observed utilization pattern. Examples from vertebrate locomotion and respiration should help to clarify and document these general ideas.

THE STRUCTURAL MECHANICS AND ECOLOGY OF THE REEF CORAL *ACROPORA RETICULATA*

Frederick Vosburgh (Duke University)

The mechanical resistance to breakage of *Acropora reticulata* determines the upper limit of species distribution in habitats exposed to wave action. *A. reticulata* is an abundant reef-building coral on Pacific Ocean atoll reefs, occuring commonly on the exposed windward reef terrace at depths where the colonies are insulated by depth from most wave action. Colonies do not occur where, based on the analysis presented here, wave action is likely to break the coral skeletons. The observed upper limit to distribution of *A. reticulata* at Enewetak Atoll corresponds to the depth at which colony skeletons are predicted to be damaged by the largest annual storm.

The depth dependent likelihood of skeletal breakage due to wave action was predicted based on the skeletal response to drag. Water velocities due to storm waves were calculated using shallow water wave theory with storm data supplied by the National Climatic Center. The hydrodynamic drag forces acting to break the coral skeletons were measured during towing tests conducted in the field at Enewetak and at the towing tank and facilities at Stevens Institute of Technology. The material properties of the skeleton were determined for fresh skeleton during mechanical testing conducted at Enewetak. Breakage of colonies *in situ* was predicted based on the water velocity for each depth, the results of the towing tests and the material properties of the skeleton.

HELICAL FIBER SYSTEMS AND BODY MECHANICS

Steve Wainwright (Duke University)

Principles of the mechanical design of helical fiber reinforcement will be stated and applied to the analysis of plant cell walls (kelp and wood) and locomotory function in animal bodies (worms and sharks). Examples range from low to high pressure systems that may be supple or stiff. The angle between the fiber and the body's axis and the interaction between fibers and matrix control changes in body shape. Fiber angle also permits certain constant volume bodies to operate with only longitudinal (nematodes) or circumferential (squid) muscles. Among the implications of these principles and observations is that the support system for shark locomotion is hydrostatic.

TWO DIMENSIONAL FINITE ELEMENT ANALYSIS OF FLOW IN CURVED TUBES *

Gautam Ray and K.B. Chandran (Tulane Medical Center)

Analyses of steady and pulsatile flow in curved tubes have been of interest to investigators in the circulatory flow dynamics due to the implications of mechanical effects as causative in atherogenesis. However, due to the complexity of the mathematical analyses, the theoretical studies have been restricted to special cases far removed from the physics of the problem. Very few experimental efforts have also been reported in the literature obviously due to the technical difficulties. In this paper, we are presenting a two-dimensional steady flow finite element solution of flow in rigid curved segments. The advantage of the finite element method is that it has the capability of including complexities of the irregular geometries and material nonlinearities. The centrifugal effects of flow in curved segments are incorporated in the solution procedure and the results are compared with the steady flow solutions in regular geometries reported in the literature to gain confidence in our technique. The geometry is then modified to represent a typical human aortic arch including taper but neglecting the arterial bifurcations, for which the results will be presented. Subsequently, the solution will be extended to represent the three-dimensional pulsatile flow in distensible tubes to simulate blood flow in arteries.

* Supported by a grant from NHLBI (HL18156)

NONINVASIVE DETERMINATION OF URETHRAL AND BLADDER PRESSURES DURING VOIDING

Dhanjoo N. Ghista and Inder Perkash (Veterans Administration Hospital, Palo Alto)

Noninvasive determination of urethral and bladder pressures can afford evaluation of (i) the urethral mechanical properties and hydraulic resistance, (ii) bladder mechanical properties and, hence, (iii) etiology of disorders of the lower urinary tract.

Background: Currently, urethral and bladder pressures cannot be monitored without inserting a catheter, which naturally alters the mechanical properties and the associated results. This paper presents the analysis for determination of urethral and bladder pressure, with the aid of the following data: (i) cross-sectional profile of the urethra (whose lumen is made opaque to x-ray by means of a contrast medium), obtained by cineradiography, (ii) urine flow rate, measured by electronic differentiation of the weight of the collected urine.

Urethral pressure: In order to determine the urethral pressure at a site (x_i) in the urethra, we formulate an energy balance equation between the site $x = x_i$ and the exit ($x = 1$) of the urethra. Accordingly, (i) the sum of the potential and kinetic energies of the urine and the strain energy of the elastic urethral tube, at site x_i, is equated to (ii) the sum of the kinetic energy of the urine at the exit ($x = 1$) and the energy loss due to viscous dissipation in the portion of the urethra between the site x_i and the exit ($x = 1$). In the resulting equation (i) the instantaneous urethral cross-sectional area A_t is known, and (ii) the velocities at x_i and 1 are expressed in terms of the monitored (and hence known) flow rate $Q(t)$. The only remaining variable in the equation is the unknown instantaneous pressure $P_x(t)$, whose value can hence be determined.

Bladder pressure: The above obtained value of the urethral pressure profile $P_x(t)$ constitutes the data input to this analysis for determination of bladder pressure. We invoke the criterion that the work done by the bladder in contracting and expelling its urine volume V ($= \int Q\,dt$) equals the sum of (i) kinetic and potential energies imparted to the urine during voiding, in the urethral length, during the voiding time, (ii) the energy loss due to viscous dissipation in the urine, contained in the urethral length, during the voiding time, and (iii) the strain energy imparted to open the urethra during voiding. The only unknown in the resulting equation, is the bladder pressure, whose value is thereby determined.

MECHANOCARDIOGRAPHY: DETERMINATION OF REGINAL CARDIAC ELASTICITY AND LEFT VENTRICULAR CHAMBER PRESSURE-FLOW PATTERNS AS DIAGNOSTIC INDICES

Gautam Ray (Southern University) and Dhanjoo N. Ghista (Veterans Administration Hospital, Palo Alto)

Mechanocardiography entails utilization of the dynamic geometry of the left ventricle to determine (i) the regional distribution of in vivo elasticity of the myocardial wall and (ii) the pressure-flow patterns in the ventricular chamber. The determination of regional variation of in vivo elasticity has enabled us to detect ischemic and infarcted myocardial areas. The pressure and flow patterns at ejection help graphically illustrate (i) the effective portion of the chamber that will contribute to the stroke volume and hence (ii) the degree by which the efficiency of the chamber contraction has been affected by the ischemia and infarct.

Data Utilization. Sequential left ventricular chamber outlines are obtained by cineangiocardiography (or by 2-d echocardiography). Based on experimental verification with markers, the loci of motions of myocardial points during a cycle are delineated. Therefrom, the myocardial wall displacement and velocity distributions are determined at the instant of each cine frame.

Analysis. Knowing the instantaneous myocardial wall chamber velocity distribution, the distribution of instantaneous pressures (normalized with respect to the pressure at the mitral valve inlet or at any other point in the chamber) along the chamber wall are determined. These boundary pressure forces constitute the instantaneous loading on the instantaneous chamber geometry. By matching the deformations of the finite element model of this instantaneous left ventricular chamber geometry (loaded by the above-mentioned pressure forces) with the monitored deformations, we obtain the instantaneous distribution of the Young's modulus of the left ventricular chamber (normalized with respect to the assumed pressure at a point in the chamber). The associated wall stresses are also determined.

Diagnostic Indices. The coefficients of the normalized diastolic modulus-stress relationship and the pressure patterns during ejection constitute diagnostic indices.

Clinical application. The above-mentioned diagnostic indices are determined for subjects with heart disease of varying etiologies. Therefrom, norms are established for the diastolic modulus-stress relationship's coefficients for normal, ischemic and infarcted myocardial elements, and characteristics patterns are established, for the chamber pressure distribution, for ventricles with normal and impaired (due to wall disease) pumping capacity. The first mentioned index helps detect ischemic and infarcted segments. The second mentioned index can help provide guidelines for decision to undertake coronary graft surgery.

A LEAST-SQUARES-FIT TECHNIQUE FOR DETERMINING JOINT CENTER LOCATIONS DURING CINEMATOGRAPHIC STUDIES OF BODY MOVEMENT

Jerome V. Danoff and Andrew Dainis (University of Maryland)

Cinematographic analysis of human movement is handicapped by the difficulty of locating positive and reproducible joint centers. Anatomical reference points have customarily been used to locate joint centers on a subject. However, non-planar movements of the subject or actual anatomical-mechanical distortions of a joint can lead to inaccuracies in these marked locations. Joint center locations are necessary as reference points for defining the orientation of limb segments which can be used to determine limb angular displacements, velocities, and accelerations.

A computer program has been developed to accept easily located points along the silhouettes of the moving limbs as input and to perform a least-squares-fitting operation to determine the overall best intersection points for each set of adjacent limbs. Data from any number of individual movie frames may be used, and the frames do not need to be sequential. The program output will list the coordinates of each joint center, the angles between adjacent limbs, and the individual limb lengths for whichever frames of the input data are requested. This method produces comparable or superior accuracy to the anatomical method in the location of joint centers and quicker and more convenient preparation of subjects.

A METHOD OF DETECTING IMPLANT LOOSENING USING X-RAY PHOTOGRAMMETRY

Frederick G. Lippert, III (Veterans Administration Hospital, Seattle); Sandor A. Veress and Ndukwe Ndukwe (University of Washington); and Richard Harrington (Veterans Administration Hospital, Seattle)

Failure of total joint replacement due to loosening of the components either between the implant and cement or between the cement and bone is emerging as a late complication with an incidence as high as thirty per cent. Loosening may not only cause pain but progressive loss of support for the prosthesis with eventual structural failure. Early diagnosis is important so that revision may be carried out when deterioration or pain occurs. No method is currently available which clearly establishes loosening at an early stage except surgical exploration. We have devised a method based on our in vivo photogrammetry studies of patellar tracking patterns using metallic markers placed in bone near both components of the total joint. Stereo x-rays taken with the joint loaded and unloaded are measured for relative motion between the implant and the metallic markers. Laboratory studies using prosthetic hip components mounted in plastic bone have revealed the ability of this method to detect movements as small as 80 microns in translation and a half of a degree in rotation. These findings were confirmed by physical measurements.

ELECTRONICS IN MOTION: TRI-PLANE ANALYZER

Joseph Ellis (California College of Podiatric Medicine)

The Tri-Plane Motion Analyzer is a recently developed device that allows the measurement and recording of the foot's motions which occur during gait. It utilizes a small 5gm sensor which attaches to any part of the foot. The sensor is small enough to allow measurements of motion even when the foot is in a shoe.

Through the use of this device several biomechanical ideas and thoughts have been proven (and others disproven). Various biomechanical treatment modalities have also been examined and checked for their effectiveness in controlling the foot's motions. This also includes different orthotic devices. In addition, twenty running shoes were tested to determine which shoes were functionally best for the athlete's feet in preventing abnormal motion, while restoring normal motion. Finally it was discovered that the foot went through different motions while on a treadmill as compared to that same subject's normal gait.

POWER PRODUCED BY MAXIMAL VELOCITY ELBOW FLEXION

Jerome V. Danoff (University of Maryland)

An analysis of horizontal elbow flexion at maximal velocity was made to determine how different loads affected power output. Thirty-three male subjects operated a specially constructed dynamometer which resisted movement with free hanging weights while allowing continuous recording of angular displacement. Subjects initially performed a maximal effort isometric trial with the elbow fully extended and then three dynamic trials at each of three loads equal to 75, 50, and 25 per cent of the maximal isometric strength.

A criterion based on consistency and magnitude of velocity was used to distinguish 20 of the subjects to be used for data analysis. The angular displacement data of these subjects were smoothed by a computerized least-squares-fit method which also produced an estimation of angular velocity and angular acceleration. Angular acceleration was used to calculate forearm torque, and power was obtained by taking the product of torque and angular velocity.

Power was found to be a cubic function of time and a fourth-order polynomial function of angular displacement reaching a peak early in the movement. The 50 per cent load resulted in a higher peak level of power than either the 25 or 75 per cent loads.

A COMPARISON OF BODY SEGMENT INERTIAS USING A MODELLING APPROACH

Robert K. Jensen (Laurentian University)

The existing mathematical models of the human body are limited by their extensive shape and mass distribution assumptions. An alternative model, based on the assumption that the body is composed of elliptical zones two centimeters wide, has been presented and in the present investigation is used to estimate the size and inertial parameters of children. Twelve boys from four age levels, four, six, nine and twelve years and three body types, endomorph, mesomorph and ectomorph, have been photographed and the coordinates needed for the elliptical zones and the joint centroids digitized. Densities as reported in the literature are assumed for the sixteen segment model. The numerical and graphical output for the program includes link diagrams, body outlines, segmental and whole body masses, moments of inertia, volumes and surface areas and mass and moment of inertia profiles. Accuracy has been evaluated by comparing the estimated and actual body masses and the error found to be less than two percent. Extensive intersubject comparisons have been made. The differences show the inadequacy of body mass and height as indicators of inertia when the body is considered as an N-link system. Segmental mass and moment of inertia ratios across ages and across body types were, in most instances, far greater than the ratios for body mass and height. These results indicate that inertial difference between children probably account for a larger proportion of the differences in motor performance than has been previously accepted.

A STUDY OF TENDON STIFFNESS AT PHYSIOLOGICAL STRAIN RATES

Wayne C. Herrick, Hebert B. Kingsbury and David Y.S. Lou (University of Delaware)

This paper describes the result of an investigation of strains and strain rates which normally occur in the tendons of the equine foreleg and presents stress-strain curves and moduli for the tendons at these rates.

It has previously been demonstrated that resistance to flexion of the joints of the distal part of the foreleg is provided by a passive system of tendons and ligaments. It is therefore possible, using a large displacement, high rate testing machine, to duplicate, in the laboratory, the strain rates and forces which are normally produced in the tendons of the foreleg of the galloping Thoroughbred racehorse.

To carry out tendon tests, legs were mounted in the test machine. The superficial flexor tendon was exposed and fitted with an extensometer and a buckle-type force transducer. Tendons of sixteen legs were tested.

It is shown that strains to 12% and strain rates to 10,000%/min occur normally in the superficial flexor tendon. Stress strain curves and tangent modulus are presented for strains from 0 to 10% at rates from 300 to 3600%/min. Tendon modulus is found to be essentially rate independent in this range.

These results suggest that tendons of human athletes may undergo much higher strains and strain rates than presently assumed.

THERMAL EFFECTS OF ORTHOPAEDIC BONE CUTTING

W.R. Krause (Montreal General Hospital)

The presence of thermal necrosis has been reported in the literature following the use of high speed burrs and saws. However, there has been very little work done in relating the different cutting parameters of orthopaedic hand tools to the temperature rise in the bone.

Controlled laboratory tests were conducted on mid-diaphysis specimens of mature bovine femur, using two different cutting burrs at 20,000 and 100,000 rpm and two reciprocating saw blades at 20,000 strokes per minute. Thermocouples were used to measure the temperature rise in the bone at various feed rates and depths of cut. The specimens were kept moist at all times but were cut with and without irrigation.

Clinical tests were also conducted using a saw blade instrumented for temperature and force. These tests were conducted during total joint arthroplasty.

The results of the cutting burrs show that the temperature decreased as the feed rate increased, and increased as the depth of the cut increased. Increasing the rotational speed of the #21 burr showed no significant differences in the average temperature measured, but the #07 burr showed a temperature increase with increasing speed. The cutting forces were observed to increase with feed rate and depth of cut, but decreased with increased rotational speed.

For the reciprocating saws at a constant feed rate, the improved design proved to cut cooler than the conventional saw blade. The effect of irrigation was dramatically seen in both the clinical and laboratory temperature results. Without irrigation, the temperature necessary to produce thermal necrosis has been seen to occur within seconds after the initiation of cutting.

USE OF A BIOMECHANICAL MODEL TO INVESTIGATE AN OCCUPATIONAL INJURY OF THE WRIST

Thomas J. Armstrong, Don B. Chaffin, F. Gaynor Evans and David A. Sonstegard
(University of Michigan)

Carpal tunnel syndrome, a compression neuropathy of the medial nerve, is believed to be caused by pressure from the extrinsic flexor tendons and from inflammations of the finger flexor synovium. A biomechanical model of the hand has been developed to study the etiology of carpal tunnel syndrome in persons performing manual work. The model can be used to describe the relationship between external forces on the hand, tensions on the extrinsic finger flexor tendons, and intrawrist tissue forces for different work positions of different sized hands. Two worker populations have been identified -- one with diagnosed carpal tunnel syndrome and one without any detectable hand or wrist ailments. Hand forces for these people are estimated via surface electromyography of the medial forearm, and hand positions are recorded via motion pictures while each individual works. This information is then used with the biomechanical model to simulate the forces which are developed in the wrist throughout the course of a normal work day. Wrist forces, as well as hand positions and forces that occur more frequently in persons with carpal tunnel syndrome are then determined statistically.

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