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UNITED STATES DISTRICT COURT

FOR THE DISTRICT OF OREGON

PORTLAND DIVISION

UNITED STATES OF AMERICA, Plaintiff, vs. CYRUS SULLIVAN, Defendant	Case No.: 3:17-CR-00306-JGZ EXPERT WITNESS REPORT WILSON C. "TOBY" HAYES, PH.D.

INTRODUCTION

1) My name is Wilson C. "Toby" Hayes, Ph.D. I have been retained as an independent expert witness by Tiffany A. Harris, Attorney at Law, on behalf of Cyrus Sullivan in the above-captioned case to provide my opinions with respect to the injuries sustained by Mr. Sullivan.

2) I have reviewed the following materials in connection with my work in this case: Multnomah County Sheriff's Office Incident Reports (6/28/17), Nine Separate Reports; Motion for Leave to Serve Subpoenas Under Rule 17(c)(3) (5/02/18); Medical Records; Radiograph CD: 6/28/17, Left Humerus, 8/3/17, Left Humerus; and Indictment (8/15/17).

3) Based on the materials I have reviewed, I understand that Mr. Cyrus Sullivan is charged with five counts of assaulting a Federal Officer related to a series of interactions with correction deputies at the Multnomah County Detention Center (MCDC) on June 28, 2017. As a consequence of these events, Mr. Sullivan was treated by paramedics at the MCDC, transported to Oregon Health & Science University Emergency Department and diagnosed by Bryan M. Wolf, M.D. with "*...an oblique fracture through the distal humeral diaphysis, with one half shaft width posterior displacement of the distal component and minimal anterior apex angulation.*" Dr. Wolf's impression was "*mildly displaced humeral diaphyseal fracture.*"

4) Two versions of how the humeral fracture occurred are reflected in the records. The Patient Care Report from the paramedics indicates that Mr. Sullivan was in "*an altercation with officers*", and stated that "*He sustained the injury when he was forced down to the ground and had his arm twisted behind his back*" and that he "*felt pain when his arm was twisted behind his back.*" Mr. Sullivan further stated that he thought "*his arm was broken after officers left his cell.*" Mr. Sullivan's version of the events was described as occurring in a cell on the fourth floor disciplinary unit (what I understand to be commonly known as "the hole"), after he had been forcefully escorted from his cell on the fifth floor in the general population area of the jail and had been pinned, face-down, by deputies to a mattress on the floor of a cell in the detention center on the fourth floor. This is when Mr. Sullivan asserts that his arm was twisted behind his back and broken.

5) The versions of these events provided by Deputy Barker and Deputy Ingram differ substantially from that of Mr. Sullivan. In his Incident Report, Deputy Barker (Incident Report, 07.15.17, MCSO) indicated that while he was "*trying to pull [Mr. Sullivan's] left arm behind his back*" [in order to handcuff him], he "*heard what [he] thought was a pop.*" He then waited for a

reaction indicating an injury and saw "*no indication of this.*" Similarly, Deputy Matthew Ingram (Incident Report, 07.13.17, MCSO) described Mr. Sullivan's resistance to having his left hand be placed behind him, hearing a "pop" noise as his left wrist "*appeared to the small of his back.*". It is my understanding that the government may argue that Mr. Sullivan's fracture occurred at the time they heard this "pop."

6) I submit this Expert Report in compliance with Rule 16(b)(1)(c) of the Federal Rules of Criminal Procedure. I expect to testify at trial regarding the matters expressed in this Expert Report and any supplemental reports or declarations that I may prepare for this matter. I may also prepare and rely on audiovisual aids, anatomic models and physical demonstrations to provide bases and reasons for various aspects of my trial testimony. I may also testify at trial with respect to any matters related to the fields of injury biomechanics or anatomy addressed by any expert testifying on behalf of the United States, if asked by the Court or by counsel.

EXPERT QUALIFICATIONS

7) Here, I provide a brief summary of my qualifications. My qualifications are stated more fully in my most recent *curriculum vitae* ("CV"), which is attached to this Expert Report as Exhibit 1.

8) I am over the age of eighteen and I am a citizen of the United States.

9) I am currently Emeritus Professor in the College of Health and Human Sciences at Oregon State University in Corvallis, Oregon. I am also President of Hayes+Associates, Inc., 2390 NW Kings Blvd., Corvallis, OR, 97330.

10) I graduated with a B.S. in Mechanical Engineering in 1964 and then an M.S. in

Mechanical Engineering (Design) in 1966 from Stanford University. As an undergraduate and graduate student at Stanford University I took courses in engineering mechanics, dynamics and kinematics and thus I am familiar with the fundamental engineering principles that are used in the reconstruction and simulation of a variety of events that can cause injuries. I received a Ph.D. in Theoretical and Applied Mechanics (Biomedical Engineering) in 1970 from Northwestern University, where my course of study involved both medical and engineering courses, the latter again including advanced training in engineering dynamics and kinematics, and the former in anatomy, physiology and biomechanics. I then completed two post-doctoral fellowships, the first at the Laboratory for Experimental Surgery in Davos, Switzerland in 1970, and the second at the Department of Orthopaedics at the Karolinska Institute in Stockholm, Sweden in 1971.

11) From 1971 to 1976, I was Assistant Professor of Mechanical Engineering and Surgery (Orthopaedics) at Stanford University. From 1976 to 1979, I was Associate Professor of Orthopaedics and Bioengineering at the University of Pennsylvania. In 1979, I was named Director of the Orthopaedic Biomechanics Laboratory at Harvard's Beth Israel Hospital and Associate Professor of Orthopaedic Surgery at Harvard Medical School. In 1983, I was named Associate Professor of Orthopaedic Surgery at the Harvard-MIT Division of Health Sciences and Technology. In 1985, I was named Full Professor at both Harvard Medical School and MIT, and then in 1988, the first incumbent of the Maurice E. Mueller Endowed Professorship of Biomechanics at Harvard Medical School, a position I held until 1998, when I joined the faculty at both Oregon State University and Oregon Health & Science University. I served as Vice Provost for Research at Oregon State from May 1998 through June 2001, when I resigned that administrative position in order to focus more fully on Hayes+Associates, Inc.

12) I have more than 40 years of teaching, research and consulting experience in fields ranging across mechanical engineering, experimental mechanics, accident reconstruction, occupant dynamics, injury biomechanics, human functional anatomy, and clinical orthopaedics. I have taught undergraduate, graduate, and post-graduate students in both engineering and medical school settings. I have lectured on the subject of injury biomechanics in a wide variety of post-graduate courses for engineers, medical students, residents, clinical orthopaedists, forensic scientists, and accident reconstructionists. At Stanford, I taught courses in engineering mechanics, experimental mechanics and biomechanics, often using examples related to injury reconstruction and injury dynamics. From 1985 to 1998 I was one of the three Course Directors of Human Functional Anatomy at Harvard Medical School. In this role, I was responsible for lectures, prosection demonstrations, and laboratory dissections, primarily related to the functional anatomy of the musculoskeletal system, including the upper extremity and elbow. I routinely made use of radiographs, MRI's, and CT's in the course of my teaching.

13) I have served as Principal or Co-Principal Investigator on 61 research grants from federal, foundation or industrial sources, all of them involving the biomechanics of the musculoskeletal system. Many of these grants directly involved injury biomechanics. Research results from my laboratory have appeared in the peer-reviewed literature and are widely cited by scientists and experts in the field. I have authored or co-authored 204 peer-reviewed publications, over 60 chapters, and two books. One of these books went through two editions. I was the founding editor of the Journal of Orthopaedic Research and served as its Co-Editor-in-Chief from 1983 to 1995. The Journal is now the preeminent research journal in orthopaedics.

14) Although I am not a licensed physician and do not treat patients, I have had considerable

experience in clinical orthopaedics. As Vice Chairman for Research in the Department of Orthopaedic Surgery at Beth Israel Deaconess Medical Center, I attended x-ray rounds, often on a daily basis, offering advice to residents and house staff on the mechanisms and treatment of musculoskeletal injuries. I served as Acting Chairman of the Department from 1992-1993 while the Department searched for a new Chief. I routinely qualify in both state and federal court in both civil and criminal proceedings to testify, to a reasonable degree of engineering and biomechanical certainty, on injury biomechanics, routinely making use of and interpreting medical histories, radiographs and anatomy as the basis for my opinions.

WITNESS'S OPINIONS

15) Based on my review and analysis of the materials provided and my background, training and experience in anatomy and injury biomechanics, it is my opinion, to a reasonable degree of engineering and biomechanical certainty, that Mr. Sullivan's humeral fracture occurred in cell 4F13 of the fourth floor detention center when he was pinned to the mattress on the cell floor by Deputies Barker & Ingram and when his arm was *"twisted behind his back."* The analysis indicates that the level of force necessary to produce such fractures are consistent with those reported in the literature as associated with motor vehicle collisions[4,20], high-intensity arm wrestling[26], and fractures known to occur during high-velocity throwing motions[31]. Moreover, it is my opinion, to a reasonable degree of engineering and biomechanical certainty, that the facts of the case rule out the version of the events provided by the Deputies, asserting that the fracture occurred in Mr. Sullivan's cell 5D23 on the fifth floor as deputies were trying to handcuff Mr. Sullivan. The fundamental bases for these opinions include: 1) The spiral configuration and twist direction of the humeral fracture itself, including its mild angulation and

displacement; 2) Peer-reviewed literature on the torsional strength of the humerus; 3) Mr. Sullivan's height and weight (and thus anthropometry); 4) Incident Reports that indicate the details of the escort process by which Mr. Sullivan was transferred from the fifth to the fourth floor; 5) My review and interpretation of the radiographs taken on June 28, 2017; and 6) My calculations, using the fundamental laws of engineering physics, that the twisting forces applied to Mr. Sullivan's forearm were both substantial and violent, applied in a manner that would be expected to cause injury, well within the capabilities of males similar to Deputies Barker and Ingram [1,5,25], and well above the reported torsional fracture strength of the humerus. These facts and analyses thus both comport with and *rule in* the assertions on injury causation provided by Mr. Sullivan and *rule out* the version of events described by the involved Deputies.

Bases And Reasons For Expert Opinions

16) The reasons and bases for my expert opinions in this case are based on my background, training and experience in the biomechanics of injury reconstruction and causation, specifically as it applies to the forces and loading mechanisms necessary to cause fractures to bone.

17) In any event involving injuries, such as the humeral fracture sustained by Cyrus Sullivan, in which the facts are in dispute, the participant and eyewitness testimony are in conflict, and no dispositive contemporaneous recording (e.g. video surveillance) is available, the injuries themselves can be used to reconstruct the mechanism of injury, help resolve factual disputes and conflicts in testimony, and thereby assist the trier of fact in the determination of responsibility. The scientific field for interpreting such injury-producing events is called *injury biomechanics* [3,7,13,17,22,28-30]; the process by which injury biomechanics is applied to particular events is called *injury reconstruction*. For an injury reconstruction to be considered scientifically reliable,

it must comport with the fundamental laws of engineering and physics (including those that apply to the human body), it must produce the injuries that were actually sustained (and not injuries that did not occur), and it must comport with the facts of the case (including, to the extent possible, eyewitness testimony). If the reconstruction meets these criteria, it can then be used to work back from the injuries, through the reconstruction, to what initiated the event and thus help determine who was at fault. Such methods are routinely used both in and outside the context of litigation and criminal proceedings to address injuries from motor vehicle collisions, falls, work-related activities, assault and abuse, and many other events.

18) Individual injury causation addresses whether a certain event produced a particular injury. Approaches to determining specific causation for the evaluation of medical conditions have been developed by organizations such as the National Institute for Occupational Safety and Health (NIOSH), the American Medical Association (AMA), the Federal Judicial Center and others [3,7,17,22] using the following steps. First, a medical diagnosis of injury must be established. Second, there must be a consistent temporal relationship between the exposure and the injury or medical condition. The third step is to compare the general knowledge to the specific circumstances of the event in question, with the focus on comparing the specific levels of exposure (as determined by a reconstruction based on engineering principles and the laws of physics) to those required to cause bodily damage. In other words, for a certain event, it must be determined whether the event produced sufficient loading to cause the injury (i.e. a scientifically reliable biomechanical mechanism). The final step is to consider modifying factors and alternative causes of the injury or condition.

19) In keeping with the above, and in particular, the causation criterion that there be an

injury diagnosis, there is no dispute as to whether Mr. Sullivan sustained a closed, displaced fracture of the distal third of the left humerus associated with the events of June 28, 2017. Direct examination of the radiographs themselves (06.28.17 and 08.03.17) further indicates that Mr. Sullivan's specific fracture is spiral in configuration, a pattern well known to occur in brittle materials such as chalk, as well as in the shafts of long bones (which are composed of cortical bone tissue, which is also a brittle material). Such fractures are known to be caused by twisting (also known as *torsion*) of long, approximately cylindrical structures such as bones. The spiral configuration of such fractures was described by Yamada (1970) as, "*The rupture starts as a spiral around the shaft and terminates as a straight line between the ends of the spiral.*" [33]. This is exactly the configuration demonstrated in Mr. Sullivan's radiographs, taken on the evening of June 28, 2017. Yamada further noted that there was a difference in the direction of the spiral, depending on whether the twist was in a clockwise or a counterclockwise direction, and that, as with Mr. Sullivan, the center of the broken part was roughly one-third of the length of the shaft, from its lower end, for the human humerus. These findings were confirmed by Klenerman (1969) [21]. I have reflected this understanding of the biomechanical mechanisms and fracture patterns associated with torsional fractures of human bone in numerous publications [2,8-12,14,15,18,19]. This long-standing understanding of the biomechanical mechanisms for torsional fractures thus allows, by direct examination of Mr. Sullivan's x-rays, taken on June 28, 2017, that his fracture was produced by twisting of his left humerus about the long axis of the bone, in a direction consistent with internal rotation of the humerus. Internal rotation is often demonstrated anatomically with the left arm, bent 90° at the elbow, with the fingers pointed forward, and the forearm rotated inward toward the belly button. In Mr. Sullivan's case, this is equivalent to the left arm, again being bent at the elbow and placed behind the back such that the

forearm is rotated clockwise (looking down from above the left shoulder) and *away* from the back. Thus, the facts of the case not only satisfy the causation criterion that a medical diagnosis be established, but also indicate that the fracture must have occurred as just described.

20) The second criterion to establish injury causation is that there must be a consistent temporal relationship between the events in question (i.e. the incidents at MCDC) and the injury or medical condition (i.e. the fracture that Mr. Sullivan sustained). This criterion is clearly in dispute, with Deputies Barker and Ingram apparently alleging that it occurred while Mr. Sullivan was standing and being handcuffed in his fifth floor cell and Mr. Sullivan asserting that it instead occurred while he was pinned to the mattress on the floor of the fourth floor cell in the detention center. Here, the configuration of the fracture fragments in the radiographs, taken shortly after the fractures were sustained, are again telling. Given the various descriptions in the Incident Reports provided by the officers involved, there was a considerable struggle as Mr. Sullivan was escorted from the fifth floor cell to the fourth floor detention center. Mr. Sullivan was variously described as "go[ing] passive", "resisting by slumping down", "resisting furiously", with Deputies Barker and Ingram performing the escort. Such a "furious struggle", which more likely than not involved the application of forces to restrain and lift Mr. Sullivan's "dead weight", is biomechanically and anatomically inconsistent with what is characterized in the medical records as a "*minimal anterior apex angulation*," "*Alignment is normal*", and an impression of "*Mildly displaced humeral diaphyseal fracture*." (Radiology Report, 6/28/17). While I would leave it to other experts to comment on whether or not Mr. Sullivan could, in the presence of a fractured humerus, mount such a violent struggle over the course of his transfer from one floor to another, his subsequent passivity just after he reported that "*I think my arm is broke* " and his "inability to rise" certainly belies the assertion that his fracture was sustained in his fifth floor cell.

21) The third criterion in a scientifically reliable injury causation opinion is to determine whether the event in question (or, in this case, which of the two events in question) produced both an appropriate mechanism and sufficient loading to cause the injury sustained (i.e. a scientifically reliable biomechanical mechanism). The simplest, and most intuitively obvious approach to predicting injury risk, makes use of the ratio between the loads imposed on an anatomic structure (in this case, Mr. Sullivan's left humerus) and the load-carrying capacity of that structure (called the *tolerance limit* or *injury threshold*). This approach to injury risk prediction can be formalized by defining a factor of risk, Φ, as the ratio of the applied torque (defined as the *twisting* effect of a force and equal to force x distance) divided by the torque necessary to cause a spiral humeral fracture. Hayes et al. [16] used this approach in describing those factors that are important to age-related fractures of the hip. For a factor of risk exceeding 1, injury to the anatomic region is more likely than not. For a factor of risk well under 1, fracture is considered unlikely. For a skeletal structure such as the humerus, determinations of the factor of risk require information both on the torques to which the humerus is subjected during loading and on the forces necessary to cause torsional fracture of the humerus. The factor of risk is a powerful and widely used approach to injury risk prediction that has been used and tested repeatedly by researchers in academia, industry and governmental agencies, and is accepted and relied upon by experts in the fields of ergonomics and injury biomechanics [6,23,24,27].

22) To implement the factor of risk in an injury causation opinion, data are required on the strength of the humerus under the loading conditions known by inspection of the radiographs to have caused the injury, in Mr. Sullivan's case, torsion. Research studies providing data on the torsional strength of the human humerus have appeared in the peer-reviewed literature since at least the late 1960's. Yamada reported the torsional fracture moment for hydrated adult long

bones as 526 in-lb, with an ultimate angle of twist of about 6° [33]. Klenerman (1969) reported the average torque at failure for fourteen humeri broken in torsion as 488 in-lb (range 195-815 in-lb)[21]. Schopfer et al. (1994) reported in seventeen intact human cadaveric humeri, torsional fracture at an average torque of 470 in-lb (range 185-885 in-lb), with an average angular rotation at failure of 26.6° (range 17.1°-38.4°)[32]. These values are in close agreement with the early data from Klenerman [21]. Lin et al. (1998) reported fracture torques of 404 ± 134 (Standard Deviation, SD) in-lb, with a failure angle of 23.7° ± 4.5°. Strothman et al. (2000) provided data on eighteen fresh frozen cadaver humeri of 467 ± 181 (SD) in-lb.

23) The data on torsional strength are used in the denominator of the factor of risk. To determine the torque actually applied in the incident involving Mr. Sullivan, we must know the length of the lever arm that can be used to apply a torque about the long axis of the humerus. Put another way, with the elbow bent at 90° and the forearm placed behind the back, the distance from the center of the elbow to the center of the wrist, represents the maximum length of the lever arm when the wrist is grasped and used to twist the humerus. Differing torques would, of course, be applied if the forearm is grasped closer to the elbow, with the most efficient application of force being at the wrist and the least efficient as the forearm is grasped closer to the elbow. Based on anthropometry (defined as the science of human size and shape) and on his height of 5'11.5", Mr. Sullivan's forearm length is approximately 10.4 inches (Exhibit 2) (AnthroCalc, 2001). Thus, for every pound of force applied at the wrist so as to twist the humerus, 10.4 in-lb of torque is applied to the humerus. Thus, to fracture the humerus in torsion, a force of between 40 and 50 pounds must be applied to the wrist and used to pull the forearm up and away from the back. These values are obviously well within the single-handed lifting capabilities for male subjects. Such forces are, of course, minimum and conservative values since

they are based on testing of cadaver bones, usually from middle-aged and elderly subjects. To fracture the left humerus of a 34-year old, 80th percentile male such as Mr. Sullivan, the applied forces were likely substantially higher (but still well within the physical capabilities of the Deputies involved.) As such, these findings demonstrate that the requirement for a scientifically reliable biomechanical mechanism is clearly met.

24) The fourth and final step to be addressed in a scientifically reliable injury causation opinion is to consider modifying factors and alternative causes of the injury, in this case the fracture to Mr. Sullivan's left humerus. Here, in the case at hand, the two alternative causal mechanisms are the fundamental questions that I have been asked to addressed, i.e. did the fracture occur as apparently being asserted by the Deputies while they were attempting to handcuff Mr. Sullivan in his fifth floor cell *before* transporting him to the detention center, or, as asserted by Mr. Sullivan, did the fracture occur *after* being escorted, while he was pinned to a mattress on the floor of a cell on the fourth floor detention center? As part of my analysis of the second criterion, i.e. objective evidence of injury, I have already noted that the aligned nature and modest displacement of the fracture fragments do not comport with the "fierce struggle" and forceful nature of the escort process as described by the Deputies. Given the lack of structural connection between the fracture fragments and the testimony that it was necessary to support Mr. Sullivan as he went limp (a process that almost certainly would have involved, at least in substantial part, the upper extremities, it would be highly unlikely for a through and through fracture of the humerus to maintain its alignment and mild displacement. In fact, the use of splints and air casts for trauma victims with serious fractures is for the very purpose of eliminating or at least reducing the relative motion and angulation of such fractures. I have also noted, although will defer to other experts on this issue, that Mr. Sullivan would likely be unable

to struggle fiercely, simply because of pain, with this serious fracture. I have already noted that Mr. Sullivan did not report that "*I think my arm is broke*" until *after* the events on the mattress in the fourth floor detention center. Finally, Deputy Barker's Incident Report (Incident Report, 07.15.17, MCSO) also comports with a fracture mechanism that occurred on the mattress of the fourth floor cell and not in the fifth floor cell. Deputy Barker's description of the fourth floor incident is that he had "*removed the right handcuff and told [Mr. Sullivan] to place his right hand under [his] belly.*" According to the Deputy, "*Inmate Sullivan would not comply with simple directions,*" and "*he had to be helped with this task by rolling him to the left a few inches.*" For Deputy Barker to use the left hand and wrist of Mr. Sullivan to roll him to his left would require that the left wrist and forearm be lifted up and away from its position at the small of Mr. Sullivan's back. This is precisely the mechanism of torque application necessary to produce the spiral fracture of the left humerus that Mr. Sullivan sustained. Moreover, in describing the events on the fifth floor, Deputy Barker indicated that he was attempting to *pull* [Mr. Sullivan's] left arm behind his back, and that Mr. Sullivan "*kept pulling up and away from [him]*" and that this is when he thought he heard a "*pop*." Such pulling actions would not apply torque to the humerus of sufficient magnitude and appropriate orientation to cause Mr. Sullivan's fracture. Thus, on the basis of the displacement and alignment of the fracture fragments, the consistent descriptions among all parties that Mr. Sullivan's complaints that his arm had been fractured occurred on the fourth floor, and the fact that Incident Report descriptions of the application of torque would produce a fracture on the mattress, rather than in the fifth floor cell, the facts and my analysis of the case lead me to conclude that the fracture occurred as Mr. Sullivan described.

Dated this 17th of August, 2018

Wilson C. "Toby" Hayes, Ph.D.

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23. Hayes, W.C.: Basic biomechanics of the skeleton. In: Twelfth Annual Applied Basic Sciences Course (eds., H.K. Uhthoff and Z.F.G. Jaworski). University of Ottawa, Canada, pp. 3-18, 1986.

24. Hayes, W.C. and Ruff, C.B.: Biomechanical compensatory mechanisms for age-related changes in cortical bone. In: Twelfth Annual Applied Basic Sciences Course (eds., H.K. Uhthoff and Z.F.G. Jaworski). University of Ottawa, Canada, pp. 371-377, 1986.

25. Hayes, W.C., et al.: Symposium: Fracture healing. In: Contemporary Orthopaedics 12(4): 69-112, 1986.

26. Cheal, E.J., and Hayes, W.C.: Finite element analysis of prosthetic ACL attachment. Pfizer Hospital Products Group. August 6, 1986.

27. Hayes, W.C.: Bone mechanics - Material properties. In: Fracture Healing. Proceedings of the Bristol-Myers/Zimmer Fracture Symposium (ed., J.M. Lane). Churchill Livingstone, Inc., New York, pp. 97-104, 1987.

28. Hayes, W.C., Nachemson, A.L., and White, A.A.: Forces in the lumbar spine. In: The Lumbar Spine (eds., M.B. Camins and P.F. O'Leary). Raven Press, New York pp. 1-21, 1987.

29. Rohlmann, A., Cheal, E.J., and Hayes, W.C.: Influence of porous coating thickness and elastic modulus on stress distribution in hip prostheses. In: Biomechanics: Basic and Applied Research (eds., G. Bergmann, R. Kolbel, and A. Rohlmann). Nijhoff Publishers, Dortrecht, Netherlands, pp. 347-352, 1987.

[28] Pierce MC, Bertocci GE, Berger R, Vogeley E. Injury biomechanics for aiding in the diagnosis of abusive head trauma. Neurosurg Clin N Am 2002; 13 155-68

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[33] Yamada H. Chapter 3: Mechanical properties of locomotor organs and tissues. In: Yamada H. Strength of Biological Materials. Baltimore, MD: Williams & Wilkins Company 1970

5/21/2018

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Date of Birth:	January 15, 1943
Place of Birth:	San Diego, California
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Education

B.S., Mechanical Engineering, Stanford University	1964
M.S., Mechanical Engineering, Stanford University	1966
Ph.D., Theoretical and Applied Mechanics, Northwestern University	1970

Postdoctoral Training

Research Fellow, Laboratory for Experimental Surgery, Davos, Switzerland (Chief, S. Perren, M.D.)	1969-1970
NIH Special Research Fellow, Department of Orthopaedic Surgery, Karolinska Institute, Stockholm, Sweden (Chief, C. Hirsch, M.D.)	1970-1971

Faculty Appointments

Instructor, Department of Orthopaedic Surgery, Northwestern University	
Assistant Professor, Department of Mechanical Engineering and (by courtesy) Department of Surgery (Orthopaedics), Stanford University	1967-1969
Associate Professor, Department of Orthopaedic Surgery, University of Pennsylvania	1971-1976
Associate Professor, Department of Orthopaedic Surgery, Harvard Medical School, Beth Israel Hospital	1976-1979
Associate Professor of Orthopaedic Surgery, Harvard-MIT Division of Health Sciences and Technology, Massachusetts Institute of Technology	1979-1985
Professor of Biomechanics, Department of Orthopaedic Surgery, Harvard Medical School, Beth Israel Hospital	1979-1985
Professor of Biomechanics, Harvard-MIT Division of Health Sciences and Technology, Massachusetts Institute of Technology	1985-1998
Maurice Edmond Mueller Professor of Biomechanics, Harvard Medical School Hospital and Administrative Appointments	1985-1998
Vice Provost for Research, Oregon State University	1998-2001
Professor of Nutrition and Exercise Science, Oregon State University	1998-2001
Adjunct Professor of Mechanical Engineering, Oregon State University	1998-2010
Professor of Orthopaedics and Rehabilitation and Vice Chair for Research, Oregon Health Sciences University	1998-2004
Emeritus Professor of Nutrition and Exercise Sciences (NES), College of Health and Human Sciences, Oregon State University	2007-

Hospital and Administrative Appointments

Chief, Biomechanics Unit, Department of Orthopaedic Surgery, University of Pennsylvania	1976-1979
Director, Orthopaedic Biomechanics Laboratory, Dept. of Orthopaedic Surgery, Beth Israel Hospital	1979
Member, Admissions Committee, Harvard-MIT Division of Health Sciences and Technology	1984-1988
Member, Committee of Professors, Harvard Medical School	1985-1989
Member, Promotions and Appointments Committee, Harvard-MIT Division of Health Sciences and Technology	1986-1998
Member, Standing Committee on Promotions, Reappointments, and Appointments, Harvard Faculty of Medicine	1987-1990
Member, Orthopaedic Executive Committee, Harvard Combined Orthopaedic Program, Harvard Medical School	1990-1998
Member, Conference of Department Heads, Harvard Medical School	1990
Member, Subcommittee of Professors, Harvard Medical School Faculty of Medicine	1991-1994
Associate Chief, Department of Orthopedic Surgery, Beth Israel Hospital	1992-1993
Vice Chairman Research, Department of Orthopedic Surgery, Beth Israel Hospital	1993

Honors and Awards

Industrial Design Society Student Merit Award	1966
Engineering Research Initiation Award, National Science Foundation	1972
Research Career Development Award, National Institutes of Health	1978-1983
Kappa Delta Award, American Academy of Orthopaedic Surgeon's Award for Orthopaedic Research	1981
American Academy of Orthopaedic Sports Medicine Research Award	1983
Research Career Award, Schweizerische Arbeitsgemeinschaft fur Osteosynthesefragen	1983-1986
Founding Fellow, American Institute of Medical and Biological Engineering	1993
American Society of Biomechanics Giovanni Borelli Award	1995
Bristol-Myers Squibb/Zimmer Institutional Grant for Excellence in Research in Orthopaedic Treatment	1996
Profiles in Ethical Integrity Award, The Program for Ethics, Science and the Environment, Department of Philosophy, Oregon State University	2000

Membership in Professional Societies

Orthopaedic Research Society	1972-
American Society of Mechanical Engineers	1975-
American Academy of Orthopaedic Surgeons, Associate Member	1985-
Society of Automotive Engineers	1998-
American Institute for Medical and Biological Engineering	2000-
International Society of Biomechanics	2002-
Association for the Advancement of Automotive Medicine	2003-
Human Factors and Ergonomics Society	2005-

Professional Activities

Member, Bioengineering and Orthopaedic Sciences Travel Group to the People's Republic of China	1979
Chairman, Program Committee, Orthopaedic Research Society	1980
Organizing Committee and Panel Member, NIH Consensus Development Conference on Total Hip Joint Replacement	1982
Member, NIH Study Section, Orthopaedics and Musculoskeletal	1985-1989
Chairperson, Special Ad Hoc Committee, National Institutes of Health Study Section	1986
Chairperson, Injury Prevention Working Group of the Surgeon General's Workshop on Health Promotion and Aging, Washington, DC	1988
Member, NIH NIAMSD National Plan Task Force, Co-Chair Musculoskeletal	1990-1991

Diseases Panel, Bethesda, MD	
Member, American Academy of Orthopaedic Surgeon's Council on Research	1990-1993
Scientific Member, AO Switzerland	1991
Member, CDC Injury Research Grant Review Committee Study Section, Atlanta, GA	1993
Co-Chairman, AAOS Workshop on Fall Prevention in the Elderly, Rosemont, IL	1993
Member, NIH Study Section, Orthopedics and Musculoskeletal	1993-1997
Participant, CDC Biomechanics Research Planning Workshop, Atlanta, GA	1994
Acting Director, AO/ASIF Research Institute, Davos, Switzerland	1996-1997
Member, National Space Biomedical Research Institute Reviewer's Reserve	1999-
Member, Scientific Advisory Board, Harborview Injury Prevention & Research Center, Seattle, WA	2005-2006
Biomechanics Research Review Panel, Biomechanics Research Portfolio Review, Centers for Disease Control and Prevention, Atlanta, GA	2009

Grants Awarded

National Science Foundation Engineering Research Initiation Award, "Stress-remodeling relationships in compact bone" Principal Investigator	1972-1973
National Science Foundation Center for Materials Research, Stanford University, "Fracture of compact bone" Principal Investigator	1972-1976
National Institutes of Health, "Mechanics of normal, arthritic and prosthetic knees" Principal Investigator	1975-1983
President's Fund, California Institute of Technology, "Mechanics of the knee joint" Principal Investigator	1975-1976
Orthopaedic Research and Education Foundation, "Flow independent viscoelastic properties of cartilage matrix" Principal Investigator	1977-1978
National Institutes of Health Research Career Development Award, "Material and structural properties of the knee" Principal Investigator	1978-1983
Veterans Administration Research Grant, "Analysis of fracture healing with internal fixation" Co-Principal Investigator	1978-1983
MIT Whitaker Health Sciences Fund, "Biomechanical studies of healing after spinal dislocation" Co-Principal Investigator	1979-1980
Laboratory for Experimental Surgery, "Mechanics of compression plate fixation" Principal Investigator	1980-1981
Zimmer USA, "Finite element and experimental studies of the Miller porous coated multi-radius tibial component" Co-Principal Investigator	1980-1981
Air Force Office of Scientific Research, "Fracture and viscoelastic characteristics of the human cervical spine" Principal Investigator	1981-1983
Howmedica, Inc., Orthopaedics Division, "Geometrical characterization of the proximal femur" Principal Investigator	1981-1982
Howmedica, Inc., Orthopaedics Division, "Effects of proximal femoral geometry on femoral component stem design" Principal Investigator	1982-1983
William F. Milton Fund, "Skeletal Aging and Exercise" Co-Principal Investigator	1982-1983
National Institutes of Health, "Stress morphology relations for trabecular bone in-vivo" Principal Investigator	1982-1983
Cintor Orthopaedic Division, Johnson & Johnson Products, Inc., "Geometrical Characterization of the distal femur" Principal Investigator	1982-1983
Cintor Orthopaedic Division, Johnson & Johnson Products, Inc., "Optimized Total Joint Replacement Designs" Principal Investigator	1982-1984
National Institutes of Health, "Bone/Gelatin Particulate Composite for Fracture Fixation" Co-Principal Investigator	1982-1984
National Institutes of Health, "Biochemistry of the Intervertebral Disc" Co-Investigator	1982-1985
Howmedica, Inc., Orthopaedic Division, "Biomechanics of the Asnis Screw System" Principal Investigator	1983-1984
National Science Foundation/Wenner Gren Foundation for Anthropological	1983-1984

Research, Inc., "Biomechanical Characterization of the Primate Femur and Tibia Using CT Scanning" Co-Investigator	
Electro-Biology, Inc., Medical Systems Division, "The Use of Pulsing Electromagnetic Fields in the Prevention of Disuse Osteoporosis" Principal Investigator`	1983-1984
General Motors Research Laboratories, "Biomechanical Studies of the Human Cervical Spine" Co-Principal Investigator	1984-1984
Johnson & Johnson, Inc. Orthopaedics, "Failure Analysis and Design Studies for a Porous-Coated Patellar Total Knee Component" Principal Investigator	1984-1985
Howmedica, Inc., "Design Parameters for Proximal Femoral Prosthetic Stems" Principal Investigator	1984-1985
Fiber Materials, Inc., "In-Vivo Testing of Carbon/Carbon Rods for Bone Ingrowth" Principal Investigator	1985-1986
National Cancer Institute, "Biomechanics of Metastatic Defects in Bone" Principal Investigator	1985-1999
Pfizer Hospital Products Group, "Finite Element Analysis of Prosthetic ACL Attachment" Principal Investigator	1985-1986
National Institutes of Health, "Hip Fracture Risk Prediction by X-ray Computed Tomography" Principal Investigator	1986-1995
General Motors Research Laboratories, "Mechanical Response and Strength of the Human Cervical Spine" Co-Principal Investigator	1986-1987
Johnson & Johnson, Inc. Orthopaedics, "Finite Element Design Analysis of a Carbon Fiber Femoral Prosthesis" Co-Principal Investigator	1987-1988
Protek, "Prosthetic Shoulder Design" Principal Investigator	1987-1988
Centers for Disease Control, "Biomechanics, Epidemiology, and Treatment of Hip Fractures" Principal Investigator	1987-1990
AO-Stiftung/ASIF-Foundation, "Fatigue Characteristics of Posterior-Lumbar Fixations" Co-Principal Investigator	1988-1989
National Institutes of Health, "Multiscan Photon Absorptiometry and Osteoporotic Fracture Risk" Principal Investigator	1989-1992
Centers for Disease Control, "Biomechanics of Hip Fracture Risk" Principal Investigator	1990-1993
National Institute of Dental Research "Mechanics and bone remodeling in an osteoporotic mandible" Co-Principal Investigator	1990-1995
Whitaker Foundation, "Magnetic Resonance Imaging of Bone Structure with Metastatic Defects in Bone" Co-Principal Investigator	1991-1994
AO-Stiftung/ASIF-Foundation, "Biodegradable Particulate Composites for Orthopaedic Applications" Principal Investigator	1991-1992
Genetics Institute, "Geometric, densitometric, and torsional properties of healing segmental defects in rat femoral tested with recombinant human BMP" Co-Principal Investigator	1991-1993
Howard Hughes Medical Institute Medical Student Research Training Co-Principal Investigator	1991-1993
National Institute on Aging, "Neuromotor changes with exercise in elderly women" Co-Principal Investigator	1991-1994
National Institutes of Health, "Hip fracture risk prediction by QDR" Principal Investigator	1991-2001
Norwich Eaton Pharmaceuticals "Effects of disphosphonates on biomechanical and morphological properties of bone in dogs" Co-Principal Investigator	1991-1992
Norwich Eaton Pharmaceuticals "Effects of NE-58095 on the biomechanical and morphological properties of bone from dogs treated for two years" Co-Principal Investigator	1992-1993
Osteonics, "Predicted effects of surface treatment on the long-term performance of cementless hip implants" Co-Principal Investigator	1992-1993
National Center for Research Resources, Shared Instrumentation Grant Principal Investigator	1992-1993

Merck, Sharp & Dohme Research Laboratories, "Evaluation of the effects of MK-217 treatment on bone biomechanics" Co-Principal Investigator	1992-1995
National Institutes of Health, "Structural consequences of post-yield behavior of bone" Co-Principal Investigator	1992-1998
DynaGen, Inc., "PPF-based biodegradable particulate composites for orthopaedic applications" Principal Investigator	1992-1993
Massachusetts General Hospital "Effects of PTH on biomechanical and morphological properties of bone in rats" Co-Principal Investigator	1992-1993
National Institutes of Health "DXA based bone geometry and osteoporotic fracture risk" Principal Investigator	1993-1998
Centers for Disease Control and Prevention, Program Project Grant "Hip fracture prevention from falls in the elderly" Principal Investigator	1993-1998
Orthopaedic Research and Education Foundation, Bristol-Myers Squibb/Zimmer Institutional Award, "Clinical biomechanics of the patellofemoral joint" Principal Investigator	1996-2001
ClinTrials BioResearch Ltd., "Bone biomechanical procedures for a long-term efficacy study of risedronate as a treatment in the osteopenic, ovariectomized rat model" Principal Investigator	1997-1998
ClinTrials BioResearch Ltd., "Bone biomechanical procedures for a long-term efficacy study of risedronate as a preventative treatment in the osteopenic, ovariectomized rat model" Principal Investigator	1997-1998
ClinTrials BioResearch Ltd., "Bone biomechanical procedures for a 26-week oral (capsule) comparative efficacy study of NE-58095 and NE-10503 in the female beagle dog" Principal Investigator	1997-1998
ClinTrials BioResearch Ltd., "A 26-week oral (capsule) fracture healing study with risedronate (NE-58095) in male and female beagle dogs" Principal Investigator	1997-1998
National Institutes of Health, "Fall Biomechanics and Hip Fracture Risk," Principal Investigator	1990-2007
National Institutes of Health "The effects of jumping on growing bones" Co-Investigator	1998-
Nike, Inc. "Functional Biomechanics of Protective Systems for Soccer: Design Criteria for Goalkeeper Gloves and Shin Guards"	2006-2007

Editorial and Review

Journal of Orthopaedic Research, Founding Co-Editor-in-Chief	1983-1995
Journal of Biomechanical Engineering, Associate Editor	1981-1985
Journal of Biomechanics, Editorial Advisory Board	1981-1983
Annals of Biomedical Engineering, Editorial Board	1980-1982
Clinical Orthopaedics and Related Research	
Critical Reviews in Bioengineering, CRC Press	
Journal of Applied Mechanics	
Journal of Bioengineering	
Journal of Biomedical Materials Research	
Journal of Bone and Joint Surgery	
National Science Foundation	
National Aeronautics and Space Administration	

Doctoral Theses Supervised

Subrata Saha, Ph.D.: Tensile impact properties of bone and their relation to microstructure, Department of Applied Mechanics, Stanford University, 1973. (Professor and Director, Orthopaedic Biomechanics Lab, Department of Orthopedic Surgery, Loma Linda University Medical Center, Loma Linda, CA)

Timothy M. Wright, Ph.D.: Tensile properties and fracture mechanics of bone, Department of Materials Science, Stanford University, 1976. (Professor and Director, Department of Biomechanics, Hospital for Special Surgery, New York, NY; Past President, Orthopaedic Research Society)

Dennis R. Carter, Ph.D: The fatigue behavior of compact bone, Department of Biomedical Engineering, Stanford University, 1976. (Professor, Department of Mechanical Engineering and Director, Biomechanics Lab, Stanford University, Stanford, CA; past-President, Orthopaedic Research Society)

Eric E. Sabelman, Ph.D: An organ culture method for study of fetal mouse bone under stress, Department of Mechanical Engineering, Stanford University, 1976. (Senior Research Associate, VA Medical Center, Palo Alto, CA)

Christopher B. Ruff, Ph.D.: Structural remodeling of the femur and tibia with aging: An automated digital analysis of the Pecos skeletal sample, Department of Anthropology, University of Pennsylvania, August 1981. (Associate Professor, Department of Cell Biology and Anatomy, Johns Hopkins School of Medicine, Baltimore, MD)

Carol A. Oatis, Ph.D.: The use of a mechanical model to predict the motion of the knee in normal locomotion: A study of healthy younger and older adult males, Department of Anatomy, University of Pennsylvania, 1982. (Associate Professor, Department of Physical Therapy, Beaver College, Philadelphia, PA)

W. Thomas Edwards, Ph.D.: A biomechanical analysis of the lumbar and lumbo-sacral spine in the sagittal plane. Interdepartmental Program in Biomedical Engineering, Massachusetts Institute of Technology, May, 1983. (Visiting Associate Professor, Department of Bioengineering, Mechanical Aerospace Manufacturing Engineering, Syracuse University, Syracuse, NY)

Anthony M. DiGioia III, M.D.: The role of interfragmentary strain in fracture healing. Harvard Medical School, Honors Thesis, March 1986. (Assistant Professor, Department of Orthopaedic Surgery, University of Pittsburgh, Pittsburgh, PA)

Edward J. Cheal, Ph.D.: Trabecular bone remodeling around implants. Massachusetts Institute of Technology, June 1986. (Director of Applied Research, Johnson & Johnson Orthopaedics, Raynham, MA)

Cheryl L. Riegger, Sc.D.: Tibiofemoral contact pressure, area and force in neutral, varus, valgus, and post-osteotomy loadings. Boston University, July 1986. (Assistant Professor, University of Colorado, Morrison, CO)

Jeffrey C. Lotz, Ph.D.: Fracture risk predictions for the human femoral neck. Massachusetts Institute of Technology, August, 1988. (Assistant Professor of Orthopaedic Surgery and Director, Orthopaedic Biomechanics Laboratory, University of California at San Francisco School of Medicine, San Francisco, CA).

Brian D. Snyder, M.D., Ph.D.: Anisotropic structure property relations for trabecular bone. University of Pennsylvania, February, 1991. (Instructor, Dept. of Orthopaedic Surg, Harvard Medical School, Boston, MA)

Dr.med. Ralf H. Wittenberg: Biomechanische und Klinische Untersuchungen dorsaler lumbaler und lumbosakraler Fusions techniken. St. Josef Hospital, Assistant Professor, Bochum University, Germany, 1991.

Xiang-Dong Edward Guo, Ph.D.: Fatigue of trabecular bone. Harvard/M.I.T. Division of Health Sciences and Technology, October, 1993. (Assistant Professor, Department of Mechanical Engineering, Columbia University, New York, NY)

Jeffrey A. Guy, M.D.: The long term effects of the bisphosphonate alendronate on the mechanical and physical properties of bone in the estrogen-deficient rat. Harvard Medical School, Honors Thesis, February, 1994. (Orthopaedic Resident, Harvard Combined Orthopaedic Program, Boston, MA)

Amy C. Courtney, Ph.D.: Mechanical properties of the proximal femur: Changes with age. Harvard-Massachusetts Institute of Technology Division of Health Sciences and Technology, May, 1994. (Staff Scientist, Department of Biomedical Engineering, Cleveland Clinic Foundation, Cleveland, OH)

Rebecca Elovic, D.M.D., Sc.D.: The effect of ovariectomy on the rat mandible. Harvard University, May, 1994. (Private practice, Brookline, MA)

Philippe K. Zysset, Ph.D.: A constitutive law for trabecular bone. Ecole Polytechnique Federale de Lausanne, Switzerland. June, 1994. (Assistant Professor, ETH, University of Lausanne, Lausanne, Switzerland)

Stephen N. Robinovitch, Ph.D.: Hip fracture and fall impact biomechanics. Harvard-Massachusetts Institute of Technology Division of Health Sciences and Technology, September, 1994. (Associate Professor and Director of the Injury Prevention and Mobility Laboratory, School of Kinesiology, Simon Fraser University, Burnaby, British Columbia)

Aya van den Kroonenberg, Ph.D.: Dynamic models of human falls for prediction of hip fracture risk. Massachusetts Institute of Technology, January, 1995. (Staff Scientist, TNO Road Vehicle Institute, Crash Safety Research Center, Delft, The Netherlands)

J. Douglas Patterson, M.D.: Parathyroid hormone (PTH 1-84) increases bone morphologic and biomechanical properties in estrogen-deficient rats: Promise for the treatment of established osteoporosis. Harvard Medical School, Honor's Thesis, February, 1995. (Orthopaedic Resident, Duke University, Durham, NC)

Michael J. Yaszemski, M.D., Ph.D.: The design, synthesis, characterization, and mechanical testing of a novel degradable polymeric biomaterial for use as a bone substitute. Massachusetts Institute of Technology, June, 1995. (Assistant Professor, Department of Orthopedics, Mayo Clinic, Rochester, MN)

Matthew J. Silva, Ph.D.: Predicting the failure behavior of the human vertebral body. Massachusetts Institute of Technology, February, 1996. (Director, Biomechanics Laboratory, Department of Orthopedic Surgery, Washington University School of Medicine, St. Louis, MO)

Catherine M. Ford Corrigan, Ph.D.: Failure of the human proximal femur: Material and structural properties. Massachusetts Institute of Technology, September, 1996. (Vice President and Principal Engineer, Exponent, Philadelphia, PA)

Steven M. Bowman, Ph.D.: Creep of trabecular bone. Harvard-Massachusetts Institute of Technology Division of Health Sciences and Technology, May, 1997. (Senior Engineer, Mitek Products, Westwood, MA)

Conrad Wang, M.D.: Densitometric and mechanical testing in an animal model of tumor-induced osteolysis in long bones. Harvard Medical School, M.D. Thesis, February, 1998. (Orthopaedic Resident, Harvard Medical School, Boston, MA)

Sara E. Wilson, Ph.D.: Analysis of the forces on the spine during a fall with application towards predicting vertebral fracture risk. Harvard-MIT Division of Health Sciences and Technology, June, 1999. (Assistant Professor, Department of Mechanical Engineering, University of Kansas, Lawrence, KS)

Cecile N. Smeesters, Ph.D.: Fall biomechanics and hip fracture risk. Division of Applied Sciences, Harvard University, June, 1999. (Professeure Adjointe, Départment de Génie Mécanique University of Sherbrook, Sherbrook, Quebec)

Jeremy J. Bauer, Ph.D.: Defining intensity of skeletal loading in children. Oregon State University Department of Nutrition and Exercise Sciences, June, 2006. (Associate, Hayes + Associates, Corvallis, OR)

Publications

A. Refereed Articles

1. Hayes, W.C. and Mockros, L.F.: Viscoelastic properties of human articular cartilage. J. Appl. Physiol., 31: 562-568, 1971.

2. Hayes, W.C.: Some viscoelastic properties of human articular cartilage. Acta Orthop. Belg., 38: 23-32, 1972.

3. Hayes, W.C., Keer, L.M., Herrmann, G., and Mockros, L.F.: A mathematical analysis for indentation tests of articular cartilage. J. Biomech., 5: 541-551, 1972.

4. Hayes, W.C. and Perren, S.M.: Plate-bone friction in the compression fixation of fractures. Clin. Orthop., 89: 236-240, 1972.

5. Saha, S. and Hayes, W.C.: Instrumented tensile-impact tests of bone. Exper. Mech., 14: 473-478, 1974.

6. Perren, S.M. and Hayes, W.C.: Biomechanik der plattenosteosynthese. Medizinish-Orthop.Technik, 2: 56-61, 1974.

7. Carter, D.R. and Hayes, W.C.: Fatigue life of compact bone. I. Effects of stress amplitude, temperature and density. J. Biomech., 9: 27-34, 1976.

8. Carter, D.R., Hayes, W.C., and Schurman, D.J.: Fatigue life of compact bone. II. Effects on microstructure and density. J. Biomech., 9: 211-218, 1976.

9. Saha, S. and Hayes, W.C.: Tensile impact properties of human compact bone. J. Biomech., 9: 243-251, 1976.

10. Hayes, W.C. and Carter, D.R.: Post-yield behavior of subchondral trabecular bone. J. Biomed. Mater. Res., 7: 537-544, 1976.

11. Wright, T.M. and Hayes, W.C.: The fracture mechanics of fatigue crack propagation in compact bone. J. Biomed. Mater. Res., 7: 637-648, 1976.

12. Carter, D.R. and Hayes, W.C.: Bone compressive strength: The influence of density and strain rate. Science, 194: 1174-1176, 1976.

13. Wright, T.M. and Hayes, W.C.: Tensile testing of bone over a wide range of strain rate: Effects of strain rate, microstructure and density. Med. Biol. Eng., 14: 671-680, 1976.

14. Wright, T.M. and Hayes, W.C.: Comments on "The elastic properties of compact bone tissue" by Reilly, D.T. and Burstein, A.H., J. Biomech., 9: 744, 1976.

15. Jones, H.H., Priest, J.D., and Hayes, W.C., Tichenor, C.C. and Nagel, D.A.: Humeral hypertrophy in response to exercise. J. Bone Joint Surg. [Am], 59(2): 204-208, 1977.

16. Carter, D.R. and Hayes, W.C.: Compact bone fatigue damage. I. Residual strength and stiffness. J. Biomech., 10: 325-337, 1977.

17. Wright, T.M. and Hayes, W.C.: Fracture mechanics parameters for compact bone. Effects of density and specimen thickness. J. Biomech., 10: 419-430, 1977.

18. Hayes, W.C. and Wright, T.M.: An empirical strength theory for compact bone. Fracture (Proc. 4th Int'l Conf. on Fracture), Volume III: 1173-1180, 1977.

19. Carter, D.R. and Hayes, W.C.: Compact bone fatigue damage. II. A microscopic examination. Clin. Orthop., 127: 265-274, 1977.

20. Saha, S. and Hayes, W.C.: Relations between tensile impact properties and microstructure of compact bone. Calcif. Tissue Res., 24: 65-72, 1977.

21. Carter, D.R. and Hayes, W.C.: The compressive behavior of bone as a two-phase porous material. J. Bone Joint Surg. [Am], 59: 954-962, 1977.

22. Hayes, W.C., Swenson, L.W., and Schurman, D.J.: Axisymmetric finite element analysis of the lateral tibial plateau. J. Biomech., 11: 21-33, 1978.

23. Hayes, W.C. and Bodine, A.J.: Flow-independent viscoelastic properties of articular cartilage matrix. J. Biomech., 11: 407-419, 1978.

24. Wright, T.M. and Hayes, W.C.: Technical note: Strain gage application on compact bone. J. Biomech., 12: 471-475, 1979.

25. Nagurka, M.L. and Hayes, W.C.: Technical note: An interactive graphics package for calculating cross-sectional properties of complex shapes. J. Biomech., 13: 59-64, 1980.

26. Woo, S. L-Y, Kuei, S.C., Amiel, D., Gomez, M.A., Hayes, W.C., White, F.C. and Akeson, W.H.: The effect of prolonged physical training on the properties of long bone. A study of Wolff's Law. J. Bone Joint Surg. [Am], 63: 780-786, 1981.

27. Ruff, C.B. and Hayes, W.C.: Subperiosteal expansion and cortical remodeling of the human femur and tibia with aging. Science, 217: 945-948, 1982.

28. Posner, I., White, A.A., Edwards, W.T. and Hayes, W.C.: A biomechanical analysis of the clinical stability of the lumbar and lumbosacral spine. Spine, 7: 374-389, 1982.

29. Ruff, C.B. and Hayes, W.C.: Cross sectional geometry of Pecos Pueblo femora and tibiae: A biomechanical investigation. I. Method and general patterns of variation. Am. J. Phys. Anthrop., 60: 359-381, 1983.

30. Ruff, C.B. and Hayes, W.C.: Cross-sectional geometry of Pecos Pueblo femora and tibiae: A biomechanical investigation. II. Sex, age and size differences. Am. J. Phys. Anthrop., 60: 383-400, 1983.

31. Beaupre, G.S., Hayes, W.C., Jofe, M.H. and White, A.A.: Monitoring fracture site properties with external fixation. J. Biomech. Eng., 105: 120-126, 1983.

32. Cheal, E.J., Hayes, W.C., White, A.A., III, and Perren, S.M.: Stress analysis of a simplified compression plate fixation system for fractured bones. J. Computers and Structures, 17: 845-855, 1983.

33. Stone, J.L., Beaupre, G.S., and Hayes, W.C.: Multiaxial strength characteristics of trabecular bone. J. Biomech., 16: 743-752, 1983.

34. Hayes, W.C., Gran, J.D., Nagurka, M.L., Feldman, J.M., and Oatis, C.: Leg motion analysis during gait by multiaxial accelerometry: Theoretical foundations and preliminary validations. J. Biomech. Eng., 105: 283-289, 1983.

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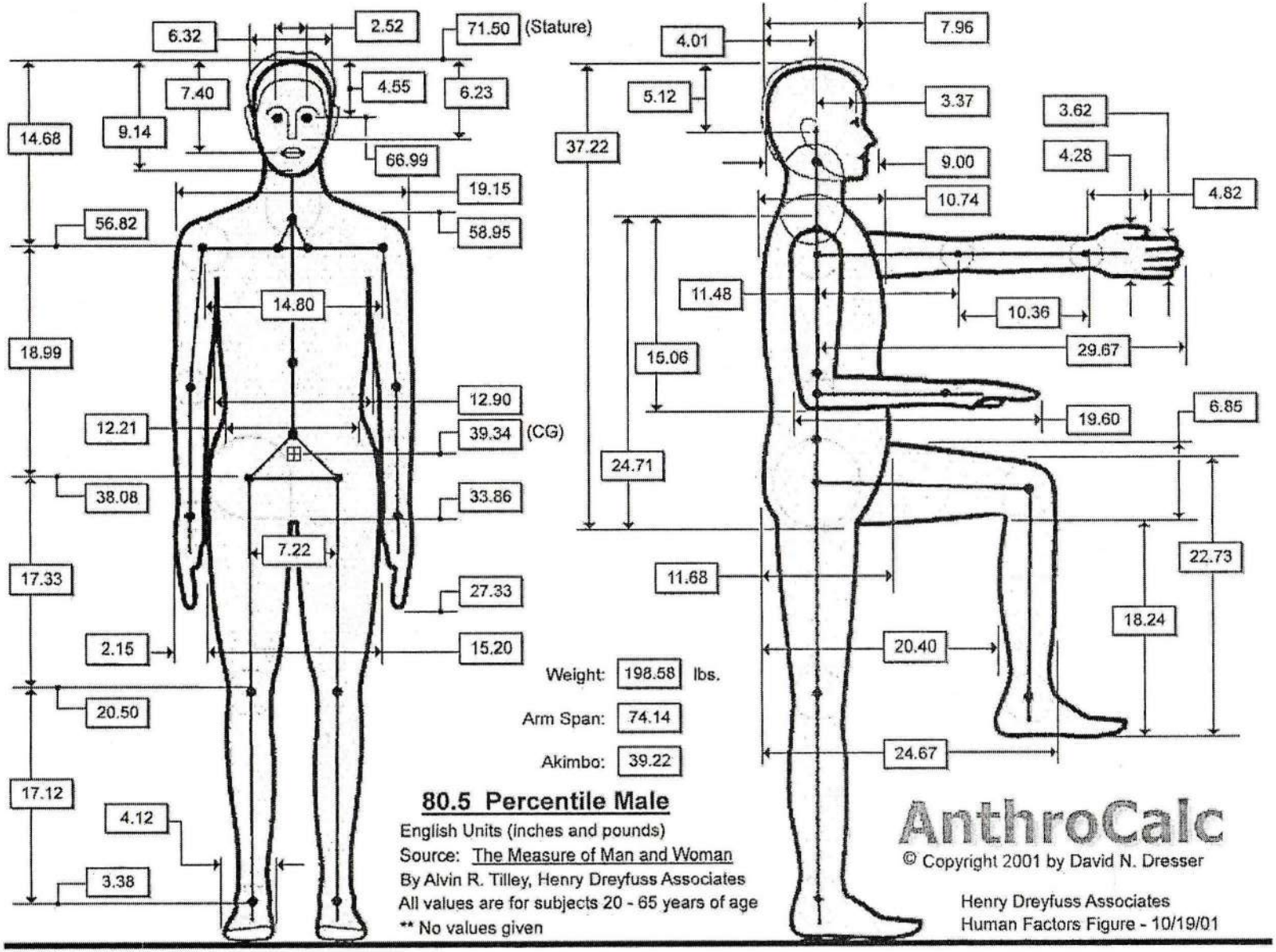
Last update: 5/18/18
Last review date: 5/16/18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