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Engineering design education and rehabilitation engineering

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INTRODUCTION

My academic career of more than 50 years has been committed to involving undergraduate and graduate students in the engineering design process [1]. A variety of experiences—childhood model making, vocational high school education, draftsman jobs, and military assignments during World War II—have convinced me that design is best learned by the necessity of reaching well-established and defined design goals during a specific time period. At MIT, first as a research engineer and then as faculty, I mounted an unending search for appropriate topics to develop into engineering design goals as well as thesis topics for my students. As part of that search I became involved in rehabilitation engineering (RE) in the late 1950s and early 1960s through a combination of prior unrelated R&D work and the influence of two individuals. A chance meeting with John Kenneth Dupress led to blindness-related projects, and an accident befalling Norbert Wiener led indirectly to my limb prostheses research. For my students as well as for me, RE proved a winner! Students were challenged technically while working on projects that had real human significance—that indeed would ultimately improve the quality of life for thousands of people. The prospect of making such contributions attracted the best students to my research projects.

MISSILES AND COMPUTERS

Prior R&D experience in missile and computer projects proved serendipitous in tackling rehabilitation projects. After my bachelor's (1950) and master's (1951) degrees at MIT (thanks to the G.I. Bill), I joined a laboratory doing R&D on air-to-air missiles.* There I began to involve students with whom I produced the internal power supplies vital to the performance of the Sparrow and Hawk missiles [2].†‡ That study involved evaluating all feasible ways of storing and converting energy in compact, lightweight packages. How else to utilize such knowledge led to a thesis topic applying the concepts to limb prostheses which produced a publication [3] and an invitation to join the National Survey Committee of the American Orthopedic and Prosthetic Association (AOPA), advising them on future prostheses possibilities, but at the time little else.

*The Dynamic Analysis and Control Laboratory (DACL), where Dr. James B. Reswick, another of the "Pioneers" in this book , was a colleague. Had Jim decided not to join the Lab Director, Professor John A. Hrones, when he moved to Case Institute of Technology, my MIT career would have been much different. John was also Head of the Machine Design Division of the Mechanical Engineering Department; Jim, not I, was John's likely successor as Head. As it was, I took over the remnant of the DACL and was appointed Head of the Division which I renamed the Engineering Design Division.

†Students engaged with me on the Missile Internal Power Systems project produced 26 bachelor's, 27 master's, 2 engineer's and 3 doctor's theses, plus my own doctoral thesis, submitted in 1957.

‡Prototype Electrical Power Units for the Sparrow I and Sparrow III missiles are in the MIT Museum collection.

Then my precollege drafting experiences and awareness of novel graphic interfaces on the Whirlwind digital computer being developed at MIT led to research with faculty colleagues and students on what we called Computer-Aided Design [4].* But missile-related design projects became less attractive for students as the missiles grew to be ballistic and intercontinental, and computer-aided design projects were thwarted by the limitations of main-frame computers and their graphics at that time, so I was searching for new areas for projects to motivate student design efforts.

SENSORY AIDS

Providentially, in 1959 John Kenneth Dupress, then with the American Foundation for the Blind (AFB), visited MIT and described communication and mobility needs of blind persons potentially amenable to an engineering approach.† These sounded eminently suitable as student projects, but as always in an academic venue, funding for research and student support was essential. John negotiated a small grant from AFB to get us started and introduced me to Mary E. Switzer, then Director of the Office of Vocational Rehabilitation of the Department of Health, Education and Welfare; OVR provided financial support for our sensory aids effort. In 1962 I outlined the potential of "Rehabilitation via Engineering Skills" [5].

BRAILLE TRANSLATION AND EMBOSSING

At this time, Braille was the only means by which the blind person could achieve literacy. With the excitement of the early digital computer age acting as a catalyst, we turned our attention to the feasibility of computer-translation of text to Grade 2 Braille, the contracted form which speeds tactile reading and reduces the volume of Braille works [6]. John Dupress served as consultant as the faculty and students wrote the DOTSYS code in Fortran using a novel segmented approach which accepted various inputs, operated on different computers, and could drive available outputs to produce embossed paper Braille [7].

Individuals and organizations external to MIT expressed an interest in DOTSYS and requested copies. We explained that the code was student-produced and certainly had "bugs." We could send a magnetic tape reel with the code but would not ask our student programmers to serve as troubleshooters. This proved less than satisfactory, but again providence intervened! The Southeastern Braille Library (SBL) in Atlanta burned, destroying its supply of Braille, badly needed by blind students and professionals in the area. In desperation the SBL asked if MIT could help; I explained that the original research, the programming of the DOTSYS code, was completed; someone else would have to refine our code to clear up any problems. Could I help if Atlanta found the requisite finances? I turned to friends at the MITRE Corporation (an MIT spin-off) who had the interest and competence to recode DOTSYS into COBOL and produce a reliable translation program. They did just that, and then one of them saw a small business possibility and formed a company named Duxbury Systems which produces and sells floppy discs with DOTSYS-based code that translates copy from any of the world's major languages into the corresponding contracted Grade 2 Braille.

Back at MIT the chain printers of the day embossed the six-dot Braille code on paper by producing lines of periods struck against a soft rubber roller. This was better than nothing, but it was not standard Braille either in scale or uniformity. A better embosser became the goal of undergraduate and graduate design theses, and the MIT Braillemboss emerged, a computer-driven Braille printer, with features borrowed from the teletypewriter equipment I had installed and maintained during my Army Signal Corps years in the United States and the Southwest Pacific!‡

*The Computer-Aided Design (CAD) project included 9 master's and 3 doctor's theses.

†Dupress had also been in the U.S. Army during World War II, was wounded by a grenade, captured by the German Army and subjected to Nazi medical experimentation. Upon his discharge he was blind with an amputated right forearm, but he completed a degree at Princeton and became Director of Technological Research at the American Foundation for the Blind. He had become familiar with the dearth of technological efforts to benefit blind persons and had a conviction that much could be done.

‡In 1972 the MIT Braillemboss received the National IR-100 Award for Innovation. The original device is in the MIT Museum collection.

Initial evaluations of the DOTSYS translation-Braillemboss system were conducted by several blind MIT students, dependent upon Braille for their schoolwork (**Figure 1**). At the National Braille Press (NBP) in Boston, where (as elsewhere) translation and embossing was done manually, we demonstrated “Jiffy” Braille. A secretary typed English copy on a Model 33 teletypewriter (**Figure 2**); the signals went over the telephone line to MIT where DOTSYS translation to Braille took place, with that signal back to NBP where the Braillemboss produced palpable Braille, all virtually instantaneously.

Understandably, individuals and organizations manually translating and embossing Braille were cautious and reticent about adopting the new technology.* We needed more demonstrations, and that required multiple Braillembossers. A cardinal rule of my assigning design projects to students is never ask them to reproduce something already extant. So we turned to another MIT-related organization, the Draper Laboratory, where the student Braillemboss design was professionalized (with funding from the Hartford Foundation) and 20 copies produced. Where did these copies go? A blind mathematician at the NASA Electronic Research Center in Cambridge, Massachusetts got a system to aid his work; a student in his master's thesis introduced and evaluated the DOTSYS-Braillemboss system in mathematics classes at the Perkins School for the Blind; another system went to the Bank of England to produce bank statements for their

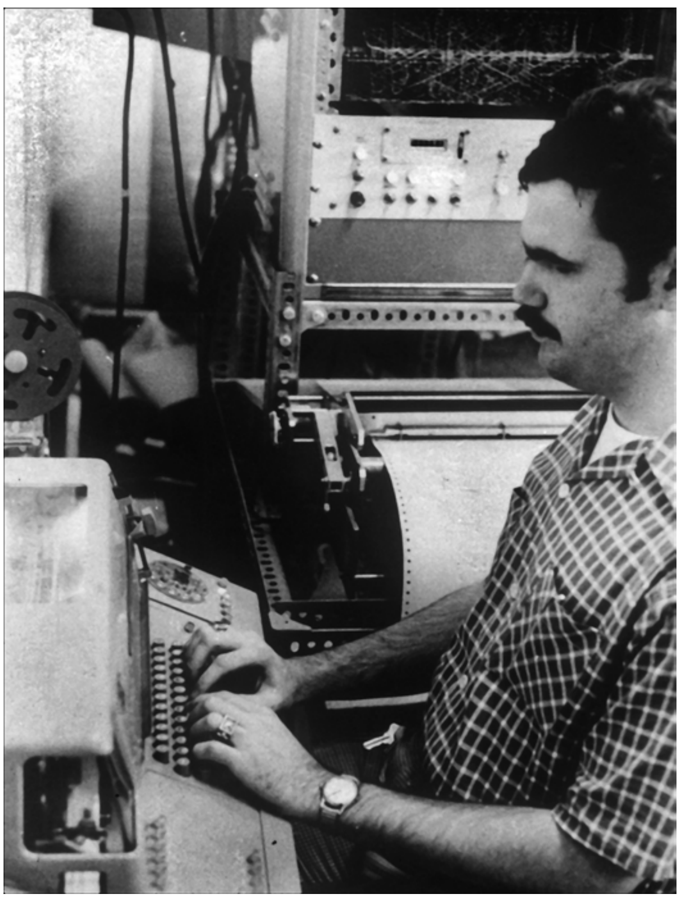

Figure 1.
MIT Master’s candidate, who is blind and a Braille reader, is using the prototype MIT Braillemboss (in the background) while on a summer job. He types on a standard teletypewriter, the signals go over telephone lines to MIT where a computer with the DOTSYS translating program translates the copy to Braille, which is then transmitted to the Braillemboss.

Figure 2.
Demonstration of “Jiffy Braille” at the National Braille Press, Inc. in Boston. For the first time a Braille producing organization could service its customers “instantaneously.” The Braillemboss is one of twenty produced in collaboration with the Draper Laboratory, Cambridge.

*Volunteers who had learned the Braille-translation code and produced single copy embossings on the manual Perkins Brailler for students and other blind persons were particularly concerned that the computer technology would deprive them of their charitable avocation. This has never proved to be the case; the need for Braille has always exceeded the supply. The National Braille Authority (NBA) that maintained the purity of the code and set the physical standards for embossing were also refractory at first. I joined the Advisory Council of the NBA and in time they became supporters of the computer revolution.

blind clients; a system went to Israel; and the Internal Revenue Service in Little Rock, Arkansas installed a system that made blind IRS agents competitive with sighted IRS representatives in answering taxpayer's questions.* Other demonstrations concurrently produced a Braille version of the daily *Wall Street Journal* news column from the same computer tape the newspaper used to print that day's text, and a novel was embossed from the same teletypesetter tape used for the book's print edition.

Our Braille hardware and software, plus our demonstrations, had the intended effect, and within a decade or so our software and Braillemboss-like printers were commercially available. Most Braille produced now is translated by DOTSYS derivatives, with the National Braille Press (NBP) among the first Braille-producing organizations to replace manual translation with computers. I have served NBP as a trustee, then as president, as has one of the students who did his master's thesis on Braille with me, and now I am an honorary trustee.

TRAVEL AIDS FOR THE BLIND

We addressed the mobility of blind travelers, ranging from an undergraduate laboratory project to improve the blind person's folding cane to electronic travel aids to advise the traveler of impediments in his path. The best of the student cane designs was improved at the Sensory Aids Center, and funding was found to purchase the swaging machinery for commercial production.† Derek Rowell continued research on the Binaural Sensory Aid (later known as the Sonic Glasses) based on his doctoral thesis at the University of Canterbury, Christchurch, New Zealand. Another ultrasonic electronic travel aid (ETA) was the invention of my MIT undergraduate classmate, Lindsay Russell, working with John Dupress at the Center. It was named the Pathsounder and went through several developmental versions and evaluations, with Russell producing it in small quantities, together with a training manual, until his death in 2000.‡

While both ETAs proved useful in improving the confident mobility of blind users, it was abundantly clear that the major problem was how best to convey to the traveler the information captured by the search apparatus of the device. Both the Binaural Sensory Aid and the Pathsounder depended on aural cues presented to the blind person's ears (the Pathsounder also had a version with a vibrator at the back of the neck strap). But one conceptual limitation was interference with ambient sounds, which a blind person depends on for safe travel more than does a sighted person. And, of course, auditory cues are useless to the deaf-blind. Our experience with cutaneous cues for kinesthetic feedback on a limb prosthesis suggested that stimulation of extensive areas of skin as an ETA display could portray a more detailed map of the space before the traveler and avoid auditory distraction [8]. The skin stimulation could be either electrocutaneous or vibrotactile; we conducted experiments on both means. Experiments were conducted that presented vibrotactile patterns on the chests of seated human subjects simulating a dynamic travel space but this work was never extended to the design and fabrication of such an ETA due primarily to funding limitations and uncertainty as to what would be the optimum display. Our developing experiences with human-interactive simulation studies of upper- and lower-limb amputation prostheses as research tools (with which to decide what best to build) argued for simulation studies to evaluate potential ETA displays. I will return to this issue.

CENTER FOR SENSORY AIDS EVALUATION AND DEVELOPMENT

When the MIT Center for Sensory Aids Evaluation and Development (CSAED) was founded in 1964 [9] John Dupress became its director. Many other projects emerged from student-staff collaboration: sound-source play balls for blind children, tools and gauges for blind auto mechanics, a sound level meter with audio output for a blind radio announcer, and so forth. The Center's activities broadened to include help to deaf-blind persons and those with low vision. For the former a tactile

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*Why Little Rock? Mary Switzer put me in touch with the Congressman from there, the Chair of the Appropriation Committee, and he was very helpful!

†One of the original student designs is on display at the MIT Museum. The Hycor Corporation of Woburn, MA, produced the MIT Cable-Cane where the design was also adapted to folding auto windshield brushes, shovels and ski poles.

‡Russell Pathsounders are on display at the MIT Museum.

communicator system (TAC-COM) was developed and deployed at the National Center for the Deaf-Blind on Long Island, NY. For visually impaired persons, a closed-circuit television (CCTV) reader resulted from two bachelor’s theses (**Figure 3**), with evaluation and further production of the CCTVs at the Massachusetts Commission for the Blind, introduced there by the first of several of our MIT engineering students who joined the Commission following their graduation.

George Dalrymple, a research engineer at the Center who contributed to many of our projects, developed a computer-driven refreshable Braille display. He and Professor Derek Rowell applied this to the AT&T Company’s Traffic Service Position System (TSPS), with a microprocessor capturing all the information from the system's visual indicators and presenting these as Braille to the fingers of a blind operator [10]. Evaluations, again in Little Rock, showed blind switchboard operators competitive with sighted peers and AT&T planned additional installations.

In 1963, due presumably to my AOPA connection, I was invited to join the National Research Council's Committee on Prosthetics Research and Development (CPRD), then exclusively oriented toward orthopedic amputation and limb prostheses R&D. I proposed the formation of a Subcommittee on Sensory Aids [11], which then sponsored a conference at the National Academy of Sciences to “survey the status of aids for the blind, review current research, and assess possibilities for future action” [12].

Figure 3.
The closed-circuit-television (CCTV) reader for the visually impaired, a bachelor thesis product by two MIT seniors. Unlike current commercial versions, the control panel I am operating with my right hand moves the copy under the TV camera.

Tragically, John Dupress died suddenly in December 1967.[*] I recruited a new Director for the Sensory Aids Center, Vito Proscia, a blind engineer at the MITRE Corporation who served the program admirably until he joined Telesensory Systems, Inc. in 1972.[†‡] Derek Rowell then became director of the Center, and when he joined the ME faculty, Dr. Michael Rosen took charge of the activities there. An evaluation at the Center of Gregg Vanderheiden's prototype AUTO-COM augmentative communication system led to the development of versatile microprocessor-based communication systems for the nonverbal motor handicapped [13], UNICOM [14] and EYE-COM [15] by Professor Rowell, George Dalrymple, Michael Rosen and Project Engineer (later Professor) Will Durfee.[§¶] Dr. Rosen also mounted a research project on upper-extremity tremor-suppression by external mechanical means [16].

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*That same year I became a Trustee of the Catholic Guild for All the Blind, founded by the Reverend Thomas J. Carroll, whose World War II Chaplain’s experiences with blinded veterans resulted in his lifelong dedication to the rehabilitation of the adventitiously blinded adult. After I become President in 1968, Father Carroll died suddenly and the Guild was renamed the Carroll Center for the Blind; see Mann RW. “Letter to the Editor” J. Rehab Res & Dev 2000;37(2): xv.

†Vito Proscia was with Telesensory Systems, Inc. through 1979, when he founded Innovative Rehabilitation Technology Inc. in Grass Valley, CA.

‡Telesensory Systems, Inc. (TSI) became the first successful commercial enterprise of which I am aware that focused its products exclusively on blindness-related products. Among these was the OPTACON, a direct-reading aid that presented a tactile image of print to the blind person’s finger, invented by Dr. James C. Bliss; see reference 18. Bliss founded TSI after his PhD at MIT with the late Professor Samuel J. Mason who, inspired by John K. Dupress, formed a Sensory Aids Group in the MIT Electrical Engineering Department. Professor Mason's group developed the original optical-character-reader input, spoken-speech output reading machine for the blind; see Mann, RW. “Letter to the Editor” J. Rehab Res & Dev 2001;38 (1):xvii.

§Dr. Rosen is now Director of the Rehabilitation Engineering Service at the National Rehabilitation Hospital in Washington, DC. He graciously assumed responsibility for the organization and editing of this “Pioneers” volume.

¶After introducing MIT students to microprocessors in his “Smart Machines” subject, Dr. Durfee moved to the University of Minnesota where he is in charge of their engineering design program.

Journal of Rehabilitation Research and Development Vol. 39, No. 6 (Supplement), 2002

Much more could and should be said about the people and projects at the MIT Sensory Aids Center, but while space does not permit, two references provide more detailed information.* When in 1970 MIT explored its role vis-a-vis engineering and living systems, I cochaired a group addressing sensory aids R&D [17]; then in 1974, I authored a chapter on the worldwide state-of-the-art in the sensory aids field [18]. But now I must shift to what becomes the second major thread of my rehabilitation engineering career—amputation prostheses—which overlapped much of my sensory aids experience.

AMPUTATION PROSTHESES

Norbert Wiener was a familiar figure on the MIT campus, through his mathematical prowess, his pioneering of cybernetics (comparing the human nervous system to the emerging fields of automatic control and computation), and his reputation as an absent-minded professor. At the time my knowledge of Dr.Wiener was limited to his absent-mindedness. So I was surprised when in the spring of 1964 I was asked if I would undertake the development of an artificial elbow. The request came from representatives of the Liberty-Mutual (LM) Insurance Company; LM sold workman's compensation insurance and thereby assumed responsibility for the rehabilitation of employees injured on the job. They ran a clinic in Boston, which fitted prostheses to amputees; orthopedic surgeons from the Massachusetts General Hospital served on the clinic staff. One of the physicians, Melvin J. Glimcher, had been greatly impressed by a "mind-activated" hand prosthesis he had seen in the USSR.† When Professor Wiener became his patient at MGH after a fall and fracture, their discussions on cybernetic prostheses led them to approach me as a design engineering faculty member already involved in rehabilitation.

I had become aware of the limb-prostheses field through my AOPA and CPRD assignments, so when LM agreed to finance the study, I asked Ronald D. Rothchild if he would take on as his master's thesis the elbow prosthesis project. He was just completing a superb bachelor's thesis on a noise-source ball for the play of blind children. Rothchild's thesis emerged as the "Boston Arm" (BA), so-called as a compromise between the claims of MGH for prompting the research, LM for funding it, and MIT for doing the R&D and producing the product.

Rothchild designed, built, and tested an artificial elbow controlled by electromyographic (EMG) signals from electrodes over the biceps-triceps musculature of the amputee's upper-arm residual limb [19] (**Figure 4**).‡ His electronic circuitry controlled the joint flexion-rate proportional to the EMG level, with force feedback requiring more exertion by the amputee for heavier loads in the terminal device. After a number of above-elbow amputees demonstrated natural control of the artificial elbow, LM was anxious for a practical wearable design. I took this on as a consulting project, LM hired two of

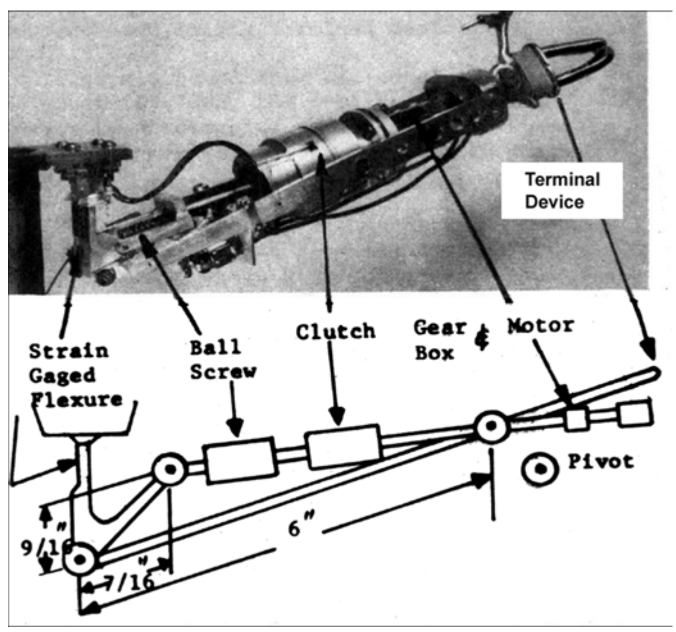

Figure 4.
The original Boston Arm, a master's thesis product, with the strain-gaged flexure as the force-sensing element. The ball-screw and clutch achieve high efficiency, while the clutch "locks" the elbow when a load attempts to back-drive the motor.

*The sensory aids effort produced about a dozen bachelors, 13 masters, and 3 doctoral theses.

†The "Russian EMG controlled Hand" was apparently a version of Dr. Reinhold Reiter's hand, developed in Nazi Germany in 1945; see Podlusky MV, Mann RW. Letters to the Editor "Forum. IEEE Spectrum, Feb 1969, and reference 22.

‡Rothchild went on to complete his PhD thesis with me on analyses and experiments on the feasibility of controlling prostheses by the detection of nerve signals (see reference 24).

my former students as staff, and at the company's facility we developed the second generation Boston Arm demonstrated at MGH in Boston, in London [20] and in Yerevan, USSR [21]. Robert B. Jerrard then did his master's thesis on the third generation design that added a powered wrist rotator and an electromechanical hand. Jerrard joined LM upon graduation and incorporated his thesis work into the next generation BA, which was then converted into a manufacturable version by T. Walley Williams III on the LM staff.* The BA continues to serve amputees, now produced by Liberating Technologies, Inc., Hopkinton, MA, a spin-off from LM.†

Critical evaluation of the BA concepts and technology in his master's thesis led Neville J. Hogan into his 1976 doctoral thesis in which he derived an optimal myoprocessor.‡ At the University of Utah, Stephen C. Jacobsen had been engaged in the artificial heart program of Dr. Wilhelm Kolff. Jacobsen came to MIT to continue that study through a PhD in fluid mechanics, but our faculty in that field were not interested in such an applied project. He became interested in the problem of how to control multijoint prosthesis in the BA natural manner for cases where the muscles for controlling the more distal joints were completely gone. He hypothesized that the musculature about the shoulder must anticipate the intent, and be prepared for the reaction forces arising from the actions of the more distal musculature; thus listening to and interpreting the EMGs from the shoulder girdle should provide the desired control information. His thesis proved his theory and he returned to Utah to demonstrate control of a multijoint prosthesis.§ But having had first-hand exposure to the BA, by then with decade-old technology, he and his Engineering Design Center at Utah produced the Utah Arm, with Jacobsen founding a company to produce it.¶

*Dr. Jerrard is now professor on the Mechanical Engineering faculty of the University of New Hampshire.

†Several early prototypes of the Boston Arm are on display at the MIT Museum.

‡Dr. Hogan subsequently joined the MIT Mechanical Engineering faculty and upon my retirement in 1992 succeeded me as Director of the Newman Laboratory. See more on his EMG processor in reference 24.

§Jerrard's 1976 PhD thesis at Utah evaluating control of the multijoint prosthesis was supervised by Dr. Jacobsen (see reference 24).

¶Professor Jacobsen's Engineering Design Center at the University of Utah and the companies he has founded have produced products including Disneyland animated manikins, medical devices, and underwater robots.

In 1970, as part of MIT's exploration of "Engineering and Living Systems," I cochaired a task group on skeletal prostheses and neuromuscular control [22]. An article in *Technology Review* introduced the general public to developments in sensory aids and limb prostheses [23]. Then in 1980 I had the opportunity to prepare a critical review of the limb prostheses field (much as I did the sensory aids area—see note [18]) when I was invited to give the ALZA Distinguished Lecture [24]. In addition to expanded versions of the foregoing descriptions of limb prostheses R&D, this article describes human-interactive computer simulations (now called virtual reality) to establish the feasibility of upper- and lower-extremity prosthesis designs, the latter by Professor Woodie Flowers in his PhD thesis, which led to the MIT Knee.**

Although Norbert Wiener's speculations on cybernetic control of prostheses indirectly precipitated what became the Boston Arm, he and I never discussed the project. His accident was in 1961, and he died in Sweden in April 1964, at just about the time I was approached by Liberty-Mutual. I did have occasion later to become quite familiar with Dr. Wiener's comments on sensory aids and prostheses when I was asked by his biographer to reflect on the consequences of Wiener's prognostications in those areas. These are recorded as part of the four volume "Norbert Wiener: Collected Works" [25]. And then at the Norbert Wiener Centenary Congress in 1994, I related Wiener's cybernetic predictions to the contemporary state-of-the-art [26].

While this summary of our efforts in the limb prostheses field is far from complete, I will conclude my memories of this period by describing a particularly engaging program.

"TOYS" FOR REHABILITATION

By the early 1970s our rehabilitation engineering efforts had achieved high visibility at MIT through the many students, mostly upper-class undergraduate and

**The MIT Knee was not commercialized, but it has been reincarnated by another group at MIT; see Mann RW, Historical perspective on IOM's role in providing a forum for discussion, in: Innovation and Invention in Medical Devices, National Academy Press, Washington DC 2001 pp. 9-12.

graduate students, who were contributing to it. Increasingly freshmen and women would ask if they could get involved, but I was wary, given their likely inexperience, both in relevant coursework and in making things. But I met an occupational therapist at a local children's rehabilitation hospital who welcomed the idea of setting our MIT students to the task of devising devices which the disabled children would see as toys, but which could also provide some rehabilitative benefit and/or augment the efforts of the occupational and physical therapists. The Creative Technological Aids (CTA) program was led by Mary Driscoll at the Kennedy Memorial (now Franciscan) Hospital and Professor Roger Kaufman and colleagues at MIT [27]. Immensely popular at both institutions, CTA produced dozens of clever devices, the invention of which challenged the MIT fresh women and men who designed and built them, while delighting the children at the hospital who played with and benefited from them. The perceived utility of some of the "toys" was such that we formed a nonprofit organization, CTA, Inc., to explore small-scale manufacture and marketing of selected devices.

Several of the toys and their originators are illustrative of the effectiveness of CTA. Dennis W. Burke, even as a freshman, dispelled my concerns with respect to fabrication ability.* A skilled craftsman, he designed and made two toys based on alphabet blocks in the MIT Hobby Shop. Each had unique coded contacts such that block placement would only close a circuit when properly oriented in the receptacle corresponding to that letter. "Bright Blocks" (**Figure 5**), had a receptacle for each of the 26 alphabetical letters. Correct placement and orientation of the appropriate block illuminated the lamp below the receptacle. "Flash Word" used the same blocks, but now the therapist drew a cartoon intended to invoke a word response, then punched the paper at the bottom of the cartoon with the code for the correct blocks. Only if the child placed the blocks so as to correspond to the word would the music box play!

Mindy Lipson was as inexperienced as I had worried freshpersons would be.† However, by observing the therapists strengthen the eye-hand coordination of the youngsters in one-on-one training, she conceived a toy to free the therapist while the child practiced. She called it "Magic Light Pen" (**Figure 6**). Only if the child kept the pen on the poster paper strip would the light in the pen stay on, providing positive reinforcement; at the end of a path the bell would ring, signifying a successful hand-eye tracing task. **Figure 7** is the production prototype of Magic Light Pen fabricated by Goodwill Industries of Harrisburg, Pennsylvania.

Figure 5.
Child at the Kennedy Memorial Hospital in Brighton, Massachusetts "playing" with the rehabilitation toy "Bright Blocks," observed by an occupational therapist.

SYNOVIAL JOINT MECHANICS

This investigation grew out of a brief discussion I had in 1966 with an orthopedic surgeon from MGH, William H. Harris. He posed a specific artificial joint replacement problem that led into a broader discussion of

*Dennis W. Burke, MD is now an orthopedic surgeon at the Massachusetts General Hospital, specializing in total joint replacement.

†Mindy Lipson Aisen, MD is now a board-certified neurologist and Director of the Rehabilitation Research and Development Service of the U.S. Department of Veterans Affairs.

Figure 6.
Child at the Kennedy Memorial Hospital in Brighton, Massachusetts practicing hand-eye coordination with the rehabilitation toy "Magic Light Pen."

human synovial joints. I was intrigued by the cartilage bearing's capacity for carrying high loads at diminishing low relative velocities of the opposing surfaces and yet exacting very small frictional losses, while (for most individuals) tolerating these difficult operating conditions for a lifetime. By comparison, human-engineered bearings—ball, needle, bronze, nylon, fluid, boundary—with which I was familiar as a design engineer, were dramatically inferior. The cartilage literature proffered numerous theories with virtually no supporting data. I set out to understand the synovial bearing as I would an engineered entity, that is, via experimental data and mathematical modeling to explain the attributes of the natural joint.

In any fluid-lubricated bearing, knowledge of the pressures developed therein is pivotal to understanding

Figure 7.
The "commercial" prototype of Magic Light Pen developed at Goodwill Industries, Inc., Harrisburg Pennsylvania.

performance. So the first issues to be addressed were the pressures on cartilage and their distribution in a typical synovial joint. The literature had no direct pressure measurements for cartilage in joints, either in vitro or in vivo. I decided that only study of cartilage in situ, intact in an actual joint loaded as in life, would produce veridical data. Choosing which joint involved two criteria. The simpler the geometry of the joint, the better; and conclusions from in vitro experiments and modeling would have to be validated in vivo. The human hip joint, a ball into a socket, met the simplicity criterion. And surgeons routinely replaced only the head of the femur with a metal endoprosthesis, the ball of which bore against natural cartilage on the socket side, the acetabulum. So if one could build an instrumented endoprosthesis, it could measure cartilage pressures in life.

In 1966 Charles E. Carlson was admitted as a graduate student with bachelor's degrees in both mechanical and electrical engineering, and he had a NSF fellowship. Carlson's master's degree explored instrumentation to fit inside the endoprosthesis ball to measure and transmit externally the pressures on acetabulum cartilage. His doctoral thesis demonstrated feasibility with an instrumented custom-designed endoprosthesis [28] (**Figure 8**). But we had to test to insure safety and we also needed to know what pressures to expect in life to calibrate the in vivo devices.*

*Space precludes describing the test and redesign processes. Suffice it here to say that while we had a feasible device in 1972, it was 1984 before all conditions of safety and performance justified human subject implantation.

Figure 8.
The prototype pressure-instrumented hip endoprosthesis, the outcome of a master's thesis feasibility study followed by a doctoral thesis, which included transducers in the load-bearing hemisphere, the electronic package for signal processing and telemetry, and the antenna at the distal end of the device.

Another graduate student, Paul D. Rushfeldt, took on the task of in vitro measurement. Preliminary data from his master’s thesis stressed the need to find a better way for surgeons to choose what size of the standard endoprosthesis ball to implant. A study recommended a gauge for the excised natural femoral head, which has become the standard orthopedic instrument [29]. Rushfeldt’s master’s thesis made clear that we needed a custom-designed testing machine for the in vitro experiments we had planned. He and Carlson designed and fabricated the MIT Hip Simulator (**Figure 9**), which became the workhorse of the project.* On it Rushfeldt ran trials with cadaver pelvito compile de novo detailed acetabula pressure data [30], and he developed a unique ultrasonic method for measuring the global geometries of the cartilage surface and that of the underlying bone, together with the cartilage layer thickness distribution [31].

Slobodan Tepic in his master’s thesis added the ability to measure the local permeability and modulus of in situ

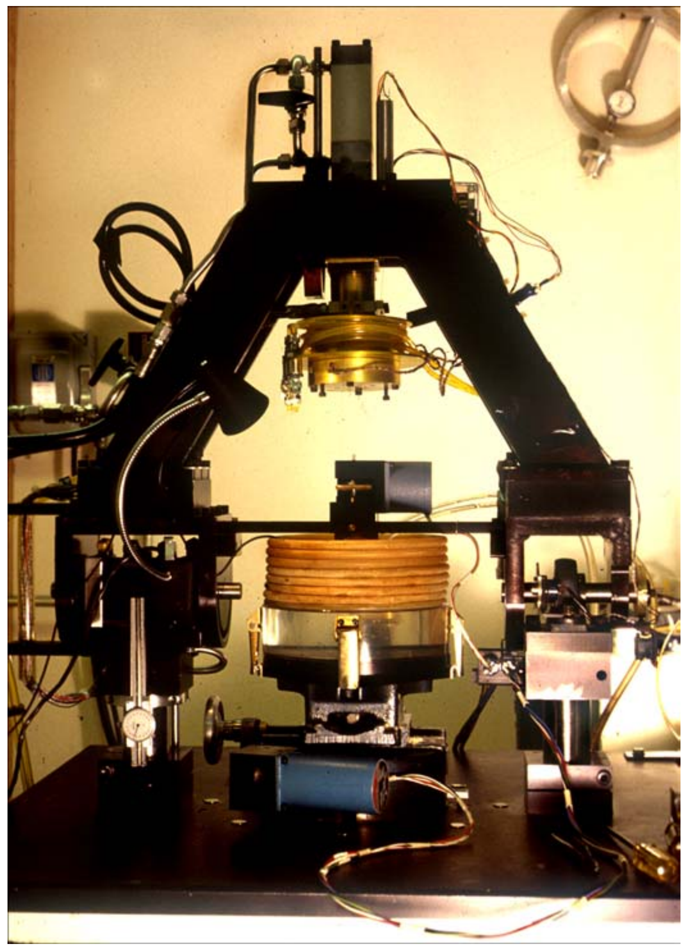

Figure 9.
The MIT Hip Simulator, a three-axis, electrohydraulic testing machine which can replicate the motions and forces at the human hip, developed by a graduate student, a research associate, and a technician.

*The MIT Hip Simulator is on display at the MIT Museum as part of an exhibit describing how MIT educates engineers and scientists.

cartilage layers and the respective distributions [32]. He made measurements of all properties of both the acetabulum and femoral head cartilage of normal cadaver joints and defined these in a mathematical model. Meanwhile Thomas Macirowski in his doctoral dissertation loaded acetabula in the Hip Simulator with an instrumented endoprosthesis for pressure data and also measured corresponding cartilage deformation with an ultrasound equipped endoprosthesis. He applied these data in finite element analyses of the cartilage layers to establish quantitatively the flow of synovial fluid from the cartilage into and through the interarticular space [33]. This information completed Tepic's computer model of an intact femoral head-acetabulum joint. Applying the kinetics and kinetics of the gait cycle to his model in a tour de force computer simulation study, Tepic produced a dynamic display of the changing pressures on the cartilage layers and the flow of fluid out of and into the joint space as the joint "walked" [34]. Through their studies Tepic and Macirowski verified quantitatively the "weeping" theory of joint lubrication proposed by McCutchen in 1959.*

The in vitro studies established our expectations for the in vivo pressure data from human implantations of the instrumented endoprostheses and determined their calibration. But the in vitro data from the Hip Simulator were based on literature sources for the loads and kinematics of human gait. To correlate the in vitro findings with the in vivo data, we would require detailed, quantitative kinematic data that captured the three-dimensional motion of the body segments of the implanted subject and kinetic data on foot-floor and intersegmental forces and torques. A long development process involving four masters theses and a doctoral dissertation, the last two by Eric Antonsson [35] produced the software named TRACK, arguably the most detailed and accurate movement analysis system ever developed [36].† As part of his PhD thesis, Antonsson also wrote software called NEWTON to calculate the intersegmental forces and torques by using TRACK kinematics, body segment mass properties and foot-floor forces. Dr. Antonsson subsequently installed an expanded TRACK system at the MGH Biomotion Laboratory where our implant systems were studied. Patrick Lord in his bachelor's and master's theses reorganized TRACK for real-time display of a prismatic representation of the subject's body segments, together with graphs of the kinematics of the several joints [37].

I said earlier I would return to the problem of how best to display information acquired by a search apparatus on a blind mobility device, an ETA, to the blind traveler. A visiting Japanese scientist applied TRACK to this problem, exploring optimum aural cues [38]. But the experiment was truncated because the viewing volume over which TRACK was accurate was only a few meters. A 1990 PhD thesis expanded that volume to some 20 meters; we anticipated further ETA studies but my retirement intervened.

Finally, we were ready for implantation in 1984. At MGH our first subject consented to accepting our instrumented device in lieu of the standard endoprosthesis. Pressure data were acquired during acute phase of recovery, through rehabilitation, and for 5 years thereafter, with synchronized pressure and gait data [39, 40]. The fully instrumented subject, here also with instrumented cane, is shown in **Figure 10**. Our second subject, for whom we have 3 years of data, was different in gender and body morphology from our first subject, but the pressure data, normalized for weight and height, are very comparable [41].‡ By and large the in vivo pressure data were similar to that from the in vitro studies, except that local pressures were surprisingly high for movements requiring cocontraction of the musculature about the hip joint for stability, such as rising from a low chair or descending stairs. In the chair-rise, our first subject generated local pressures as high as 18 MPa, whereas in the stance phase of gait the typical highest pressure is 5 MPa.§

Earlier research, modeling the musculature of the entire lower extremity and applying gait analysis [42], had suggested a greater role for cocontraction than has generally been assumed. Any inverse-Newtonian-based analyses of joint force using kinematic data cannot account for cocontraction since the cocontraction components of muscle force do not produce motion about the joint. To accomplish the muscle-model analysis properly we have designed and fabricated several new endoprostheses that measure directly the forces at the hip.

*McCutchen CW. Mechanism of animal joints: sponge-hydrostatic and weeping bearings. 1959 Nature; 184:1284-1285.

†Professor Antonsson is currently the head of the Mechanical Engineering Department at the California Institute of Technology.

‡Dr. David E. Krebs had become Director of the Biomotion Laboratory. A number of his masters' candidates in physical therapy at the MGH Institute of Health Professions conducted their theses on the Hip Project.

§Our unique pressure data are being applied to research on how cartilage and the chondrocyte cells, which nurture the tissue, respond to regimens of dynamic pressure variation.

Journal of Rehabilitation Research and Development Vol. 39, No. 6 (Supplement), 2002

Figure 10.
A subject at the Massachusetts General Hospital with the pressure-instrumented endoprosthesis in her right hip joint and her motions and foot-floor forces concurrently measured by the MIT TRACK system. The electro-optical cameras detect the light-emitting diodes (LEDs) imbedded in arrays fastened to each body segment. Even the cane is force instrumented.

Since this Hip Project started in 1966 and continues now a decade after my 1992 retirement, space here precludes doing justice to all the contributors.[*]

NEWMAN LABORATORY FOR BIOMECHANICS AND HUMAN REHABILITATION

"Technology designed to rehabilitate humans, based on fundamental understanding of the underlying physiology and biomechanics, constitutes one of the major foci of biomedical engineering research in the Mechanical Engineering Department".[†] By the 1970s our program required more space, which (as any academician knows) is perhaps the most contested commodity. In addition to NIH, NSF, and VA grants, plus funding from a number of foundations, in 1972 I became Director of one of the first five rehabilitation engineering research centers (RERCs). In 1959 I had restructured the antiquated Heat-Power Laboratory which occupied prime space in the ME Department into the Engineering Projects Laboratory (EPL) to get our undergraduates conducting their laboratory exercises on current sponsored R&D projects. I introduced more and more of our rehabilitation projects into the EPL until around 1975, when I made the case that part of the EPL space should be devoted to rehabilitation. Then I had the good fortune to give a lecture on our hip project in Saint Louis and acquired the strong support of a local MIT alumnus who made a very generous gift to MIT. This gift made possible a dramatic redesign of the entire former EPL space into the Newman Laboratory for Biomechanics and Human Rehabilitation.

An ongoing exhibition at the MIT Museum, "Mind and Hand: The Making of MIT Scientists and Engineers," characterizes the Newman Laboratory as a paradigm of the MIT style of integrating education and research. The display cases include folding canes and ETAs for the blind, prototype Boston Arms, the original Magic Light Pen, and the Hip Simulator with instrumented endoprostheses. The Laboratory bibliography cites 241 bachelor, 168 masters, and 56 doctoral theses conducted within Newman. Among these are the doctoral theses of three current MIT Mechanical Engineering faculty as well as those of seven others who now serve as faculty at other universities and who continue their effectiveness in rehabilitation-related research. In addition to those students directly involved in the Lab over the decades, our visibility enhanced the entire university community's sensitivity to disabling conditions.

[*] An incomplete and unpublished record, "Understanding Synovial Joint Biomechanics: Implications for Orthopedic Surgery, Physical Therapy and Rehabilitation, and the Etiology of Osteoarthritis," now has 80 pages of text and 372 references, including 55 SB, 42 SM, 1 ME, 22 PhD and 1 MD theses.

[†] This quote is from the Annual Report Academic Year 1979–1980, Department of Mechanical Engineering, Massachusetts Institute of Technology, page 30.The Annual Reports of the Department, which in my library go back to 1972–1973, are an excellent source of more detail on projects abstracted in this article.

PERSONAL REFLECTIONS

Rehabilitation engineering research and development have served both my students and my own academic career well. Beyond space acquisitions for the Sensory Aids Center and the Newman Laboratory, I was promoted to full professor in 1963, when I was well into the blindness research, and I was appointed to two endowed chairs, the Germeshausen, then the Whitaker. Through collaboration with health professionals I expanded my experiences beyond those traditional for MIT faculty. On John Dupress' advice I eased into that relationship. When in 1958 he proposed I shift from missiles and computers to blindness problems I wondered with him why I should choose that area among the vast opportunities in biomedical engineering. He offered this aphorism: "An ophthalmologist is to a blind man as a general practitioner is to a corpse." To wit, in blindness-related R&D you won't need to deal with doctors! Later when collaborations developed with orthopedic surgeons in the Boston Arm project and then the Hip Project, I appreciated my easy entrance into rehabilitation.*

The foothold I had acquired in biomedical engineering though the blindness-related R&D gave me both the experiences and the credentials to transition easily into collaborations with orthopods.

My medical connections broadened beyond rehabilitation into medicine more generally, when in the late sixties and early seventies MIT and Harvard University began to explore a collaborative effort in the health field. In 1972 I became the only nonadministration member of the Executive Committee forming the Harvard-MIT Program in Health Sciences and Technology, which became the HST Division; I still hold an appointment as Professor in HST and therefore as an Officer of Instruction at Harvard University. For over a decade I served on the HST MD Curriculum Committee, attempting to introduce mathematical and physical science into subjects HST students took at Harvard Medical School.† My medical associations likely helped my election to the Institute of Medicine of the National Academy of Sciences in 1971, the first engineer so honored. And my election as the first member of the MIT ME Department to the National Academy of Engineering (NAE) in 1973 might in part be traced to my forming and chairing in 1963 the Subcommittee on Sensory Aids of the Committee on the Interplay of Engineering with Biology and Medicine of the NAE. Then the most surprising of all for a design engineer, I was elected to the National Academy of Sciences in 1982. At the time only five other persons had been elected to all three honoraries.‡ Rehabilitation engineering was not a deterrent to recognition!

My long involvement in rehabilitation research, development, policy, and service delivery brought into focus for me sweeping changes in the American public's perceptions on race, gender, and health. To oversimplify, there was a time when the hallmarks of Americans were Caucasian, male, healthy. The turmoil of the 1960s taught us to accept ethnicity, then recognize the contributions women have and can make to society, and finally note that a significant fraction of our population experienced disabling conditions.‡¶**††

In reports describing my retirement, though the illustrations were of former and recent colleagues and students and of rehabilitation engineering projects we had

*In 1971, I was appointed to the Harvard Medical School Executive Committee on Rehabilitation Planning and in 1972 to the Harvard Medical School Dean's Committee for West Roxbury Veterans Administration Hospital. I came to realize that rehabilitation medicine and physiatrists were not highly regarded then, especially among orthopedic surgeons. A Department of Physical Medicine and Rehabilitation was finally formed at the Harvard Medical School in November 1995.

†I also participated in organizing collaborative research between MIT faculty and physicians at Harvard Medical School and associated hospitals. In 1972 I became the Principal Investigator of a Program Project Grant funded by the National Institutes of Health titled, "An Interdisciplinary Program in Biomaterials Science."

‡I have also been elected Fellow in the American Academy of Arts and Sciences, the American Association for the Advancement of Science, the Institute of Electrical and Electronic Engineers, the American Society of Mechanical Engineers, and I am a Founding Fellow of the American Institute of Medical and Biological Engineers. Other rehabilitation-related recognitions include those from United Cerebral Palsy, the ASME Gold Medal and inaugural H. R Lissner Award, the Associated Blind of Massachusetts, Sigma Xi National Lecturer.

¶In 1995 I was the inaugural faculty recipient of the MIT Reverend Dr. Martin Luther King, Jr. Leadership Award, for "achievements and contributions exemplifying the ideals of Dr. King."

**In 1946–47 my entering freshman class was comprised of 907 men (none Black that I can remember) and 7 women. Now 41 percent of MIT undergraduates are women (27 percent among graduate students and much too low in faculty ranks), while minorities are reasonably represented among students but far too few among faculty.

††When I began my blindness-related research in 1958, I sought cooperation with the deafness community. I was exasperated to learn that the two groups saw no common cause; rather they squabbled over the sparse resources extant. That too has changed.

worked on, I was pleased with the titles the authors had chosen. “A Designer's Designer” [43] and “A Life in Design” [44]. But my greatest and most lasting satisfaction derives from the myriad of marvelous students I have had the pleasure of teaching and advising. I have learned more from them than I have taught them.

EPILOGUE

In 1990, to plan for an orderly transition of Newman Laboratory leadership, I told the head of Mechanical Engineering that I intended to retire in July of 1992. We discussed (and I documented) my preference that an associate professor clearly qualified for tenure succeed me as Laboratory Director and the principal research scientist take over my role as Director of the Rehabilitation Engineering Research Center. When a new chairman took over the department in July of 1991, I pressed him to consider the proposed changes, noting that “the Newman Laboratory involves five faculty, a principal research scientist, and over 40 graduate student research assistants, occupies prime space in the Department, and is very visible and oft visited.” Nothing happened. Then in the spring of 1992 I learned that the new head, without my knowledge or consultation, was planning major changes for the laboratory. His intentions became clear when he thwarted the tenure prospects of my proposed successor and indicated to the principal research scientist that he had no future at MIT. When I challenged him as to what he was about, his reply was “there is no money in rehabilitation”! Thus the human rehabilitation program described above has shrunk to one project and the Laboratory that bore that name is now but a faint shadow of its former self.

REFERENCES

1. Mann RW. Engineering design education U.S.A.: Retrospective and contemporary. Trans ASME, J Mech Design 1981;103(4):696–701.
2. Mann RW. U. S. Patent Application Serial No. 855,243 Electrical power unit, filed in security Nov 24, 1959. Issued as U.S. Patent No. 3,230,381, Jan 18, 1966 with SK Grinnell.
3. Paul I, Mann RW. Evaluation of energy and power requirements for externally powered upper-extremity prosthetic and orthopaedic devices. 1962; ASME 62-WA-121.
4. Mann RW, Coons SA. Computer-aided design. In: McGraw-Hill Yearbook Science and Technology, New York: McGraw-Hill; 1965; 1–9.
5. Mann RW. Rehabilitation via engineering skills. Rehabilitation Record 1962; 3(1), Office of Vocational Rehabilitation, Dept. of Health, Education & Welfare, Washington, DC; 22–4.
6. Mann RW. Enhancing the availability of Braille. Proc Internat Cong Tech and Blindness, New York: American Foundation for the Blind, 1963; 1:409–26.
7. Mann RW. A comprehensive, computer-based, Braille translating system. 7th Internat Conf Med Bio Eng; Stockholm, Sweden: Almqvist & Wiksell Booksellers, 1967, p. 363.
8. Mann RW. Mobility aids for the blind–An argument for a computer-based, man-device-environment, interactive, simulation system. Pro Conf on Evaluation of Mobility Aids for the Blind, Washington, DC: Com. on Interplay of Eng. with Biology and Medicine, National. Academy of Engineering., June 1970, pp. 101–16.
9. Mann RW. The establishment of a center for sensory aids evaluation and development. Proc Mobility Res Conf, Rotterdam, The Netherlands, New York: Am. Found Blind, 1965, 173–90.
10. Dalrymple GF. TSPS braille display. Braille research newsletter, No 6, eds: JM Gill, .LL Clarke, U Warwick and Am Found Blind, Oct 1977: 78–81.
11. Mann RW. The role of the subcommittee on sensory aids of the committee on prosthetics research and development of the national academy of science--National research council USA. Internat Conf Sensory Devices Blind. St. Dunstans, UK 1966: 435–38.
12. Sensory aids for the blind, Washington, DC, NAS Pub 1691, 1968.
13. Goodenough-Trepagnier C, Rosen MJ. An analytical framework for optimizing design and selection of non-vocal communication techniques, Trans IFAC conf control aspects of prosthetics and orthotics, 1982, Columbus, OH
14. Rowell G, Dalrymple GF, Olsen J. Unicom: A universal communication system for the non-verbal motor impaired. Proc fifth annual conf systems and devices for the disabled, 1978, Houston TX.
15. Rosen MJ, Durfee WK. A preliminary report on EYE-COM, an eye movement detection and decoding system for non-vocal communication, Proc fifth annual conf systems and devices for the disabled, 1978, Houston TX.
16. Rosen MJ, Arnold AS, Baiges IJ, Aisen ML, Eglowstein SR. Design of a controlled-energy dissipation orthosis for functional suppression of intention tremors. J Rehabil Res Dev 1995 Feb; 32 (1): 1–16.
17. Mann RW, Troxel DE. Task group on sensory aids. In: Engineering and Living Systems—Interfaces and Opportunities, Cambridge, MA: The MIT Press, 1970: 245–69.

18. Mann RW. Technology and human rehabilitation: prostheses for sensory rehabilitation and/or sensory substitution, in Advances in Biomedical Engineering, Vol. 4, New York: Academic Press, Inc., 1974, 209–353.
19. Rothchild RD, Mann RW. An EMG controlled, force sensing, proportional rate, elbow prosthesis. Proc Symp Biomed Eng, Marquette Univ., Milwaukee, WI, Vol. I, 1966,106–9.
20. Mann RW. Efferent and afferent control of an electromyographic proportional-rate, force sensing artificial elbow with cutaneous display of joint angle, Symposium on the Basic Problems of Prehension, Movement and Control of Artificial Limbs, Proc Inst Mech Engrs., Vol. 183, Pt. 3J, London: Inst Mech Eng, 1968–69, 86–92.
21. Mann RW. Design criteria, development and pre- and post-fitting amputee evaluation of an EMG controlled, force sensing, proportional-rate, elbow prosthesis with cutaneous kinesthetic feedback. Technical and Biological Problems of Control - A Cybernetic View, Pittsburgh, PA: The Instrument Soc. of America, pp. 579–86, 1970; also published in Russian in Vol. 2, Bioelectric-Controlled Man and Automatic Systems. Proceedings of the International Federation of Automatic Control Cybernetics Conference, Yerevan 1968, Moscow, 1970
22. Mann RW, Glimcher MJ. Task group report on skeletal prostheses and neuromuscular control, in Engineering and Living Systems - Interfaces and Opportunities, Cambridge, MA: The MIT Press, 1970, 271–83
23. Mann RW. Technology for human rehabilitation in Technology Review, 1978; 81 (2), Cambridge, MA: M.I.T., November, 1978, pp. 44–52.
24. Mann RW. Cybernetic limb prostheses: The ALZA distinguished lecture. Annals Biomed Eng; 9 (1)1981, pp. 1-43; Yearbook Soc Gen Sys Res, ed Rammohan K. Ragade, Univ. of Louisville, Louisville, KY, Soc Gen Sys Res, Vol. XXVI, 1981,159–201.
25. Mann RW. Commentary on the Prostheses-Oriented Papers of Norbert Wiener, in Norbert Wiener: Collected Works, edited by P. Masani, Cambridge, MA: M.I.T. Press, September, 1986, pp. 432–40.
26. Mann RW. Sensory and motor prostheses in the aftermath of Wiener in: Proceedings of Symposia in Applied Mathematics, pp. 401–39, Vol. 52, 1997, American Mathematical Society.
27. Dalrymple GF, Kaufman RE, Driscoll M, Kamil N. Bridging the humanist-mechanist gap: Creative technological aids for the disabled. Conf systems and devices for the disabled, 1976, Boston MA.
28. Carlson CE, Mann RW, Harris WH. A radio telemetry device for monitoring cartilage surface pressures in the human hip, IEEE Trans Biomed Eng. 1974; BME-21 (4):257–64
29. Harris WH, Rushfeldt PD, Carlson CE. Scholler J-M, Mann RW. Pressure distribution in the hip and selection of hemi-arthroplasty, In: The Hip: Proceedings of the Third Annual Open Scientific Meeting-The Hip Society, 1975, St. Louis: C. V. Mosby,, pp. 93–8.
30. Rushfeldt PD, Mann RW, Harris WH. Improved techniques for measuring in vitro the geometry and pressure distribution in the human acetabulum Part II: Instrumented endoprosthesis measurement of articular cartilage surface pressure distribution. J Biomech 1981;14 (5):315–24.
31. Rushfeldt PD, Mann RW, Harris WH. Improved techniques for measuring in vitro the geometry and pressure distribution in the human acetabulum, Part I: Ultrasonic measurement of acetabular surfaces, sphericity and cartilage thickness. J Biomech 1981;14(4):253–60.
32. Tepic S, Macirowski T, Mann RW. Mechanical properties of articular cartilage elucidated by osmotic loading and ultrasound. Proc Natl Acad Scs USA 1983:80:3331–3.
33. Macirowski T, Tepic S, Mann RW. Cartilage stresses in the human hip joint. J Biomechanical Eng 1994:116:10–18.
34. Tepic S, Macirowski T, Mann RW. Simulation of mechanical factors in human hip articular cartilage during walking. Proc. of the 1984 Summer Computer Simulation Conf. Boston, MA, Ed: William Wade, Vol. 2, La Jolla, CA: Soc. for Comp. Sim., July, 1984, pp. 834–39.
35. Antonsson EK, Mann RW. “Automatic 6-D.O.F. kinematic trajectory acquisition and analysis. J Dynamic Systems, Measurement., and Control 1989;111:31–9.
36. Rowell D, Mann RW. TRACK© - The MIT Movement Analysis System, A Benchmark with which to Compare Commercially Available Data Processing Methods, In: International. Symposium on Gait Analysis., State-of-the-Art of Measuring Systems and Their Implication in Prosthetic & Orthotic Technology, Ed. U. Boenick, M. Näder, C. Mainka, Tech. U. Berlin, Berlin, Germany, Feb., 1990, pp. 150–65.
37. Rowell, Mann RW. Human movement analysis--Optoelectronics, LED arrays, and software produce rapid automatic, and precise 3-D position and orientation kinematics and dynamics. SOMA, 1989; 3 (2):13–20.
38. Tachi S, Mann RW, Rowell D. Quantitative comparison of alternative sensory displays for mobility aids for the blind. IEEE Trans Biomed Eng. 1983; BME 30(9):571–7.
39. Hodge WA, Fijan RS, Carlson KL, Burgess RG, Harris WH, Mann RW. Contact pressures in the human hip joint measured in vivo. Proc Natl Acad Scs USA; May, 1986: 2879–83. See also:Lewin R. Pressures measured in live hip joint. Science1986; 232:1192–3.
40. Hodge WA, Carlson KL, Fijan RS, Burgess, RG, Riley PO, Harris WH, Mann RW. Contact pressures from an instrumented hip endoprosthesis. J Bone Jt Surg 1989; 71-A(9)1378–86.

41. Carlson KL. Human hip joint mechanics - An investigation into the effects of femoral head endoprosthetic replacements using *in vitro* and *in vivo* pressure data. PhD Thesis, Dept Mech Eng, MIT May 1993.
42. Patriarco AG, Mann RW, Simon SR. Mansour JM. An evaluation of the approaches of optimization models in the prediction of muscle forces during human gait, J Biomech 1981;14 (8):513–25.
43. Andrews DW. Robert Mann,’50 - A designer’s designer. Technology Review February/March1993 pp. MIT 7-9.
44. Pease T. A life in design: Newman lab director Bob Mann retires from a 41-Year MIT career that ran the gamut from missiles to muscles. MIT Spectrum Spring 1992 pp. 10–12.