From Design to Research: Upper Limb Prosthetic Research and Development in Canada, 1960-2000

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Abstract: This paper examines the history of the research and development (R&D) of myoelectric upper limb prosthesis in Canada from 1960 to 2000. It focuses on two of the prosthetic research and training units (PRTUs) that were created and funded by the federal government as a result of the Thalidomide tragedy: the Rehabilitation Centre at the Ontario Crippled Children's Centre (OCCC) and successor organizations, and the University of New Brunswick's (UNB) Institute of Biomedical Engineering (the Institute or IBME). Both developed commercial systems for myoelectrically controlled arms and hands. We argue that, in contrast to the common view that research in universities and public research institutions has increasingly moved away from basic problems and to product development and commercialization over the period, research in this field has moved in the opposite direction. We explore these cases in detail and examine the forces at work in this change from a design-oriented approach to one that became research intensive.

Résumé : Cet article examine l'histoire de la recherche et développement (R & D) pour les prothèses myoélectriques de membres supérieurs au Canada de 1960 à 2000. Il se concentre sur deux des unités recherche et de formation sur les prothèses (PRTUs) qui ont été créées et financées par le gouvernement fédéral à la suite de la tragédie de la thalidomide: le Rehabilitation Centre au Ontario Crippled Children's Centre (OCCC) et les organisations qui lui ont succédé, et le University of New Brunswick's (UNB) Institute of Biomedical Engineering (IBME). Les deux ont développé des systèmes commerciaux pour des bras et des mains à commande myoélectrique. Nous soutenons que, contrairement à l'opinion commune à l'effet que la recherche dans les universités et les institutions publiques de recherche s'est de plus en plus éloignée des problèmes fondamentaux pour se concentrer sur le développement et la commercialisation de produits, la recherche dans ce domaine a évolué dans la direction opposée. Nous explorons ces cas en détail et examinons les forces à l'œuvre dans ce changement d'une approche axée sur la conception vers une approche devenue intensive en recherche.

Introduction

The idea that research at universities and public institutions has recently changed from a focus on scientific discovery to knowledge production has found expression in a variety of theories of profound changes in scientific cultures. Advocates of the changes include the authors of the concepts of mode 2 knowledge production, knowledge translation, and the triple helix of university-industry-government relations.[1] In the

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[1] M. Gibbons, C. Limoges, H. Nowotny, S. Schwartzman, P. Scott, and M. Trow, The New Production of Knowledge: The Dynamics of Science and Research in Contemporary Societies (London: Sage, 1994); H. Nowotny, P. Scott, M. Gibbons, Re-Thinking Science: Knowledge and the Public in an Age of Uncertainty (Cambridge: Polity Press, 2001); H. Etzkowitz, "Research groups as 'quasi-firms': the invention of the entrepreneurial university," Research Policy 32, (2003): 109–121; H. Etzkowitz and L. Leydesdorff, "The endless transition: A "triple helix" of university–industry–government relations," Minerva 36, (1998): 203–

language of the mode 2 concept, which has emerged as the "normal science" of the R&D and innovation studies research field, the transition consists of a change from the old paradigm of "scientific discovery" (mode 1) to the new one of "knowledge production" (mode 2).[2] The old approach consists of experimental science, internally driven by autonomous, university and discipline-based researchers. In contrast, the new knowledge is produced through socially distributed, application-oriented, trans-disciplinary projects, subject to multiple accountabilities and performed in "contexts-of-application."

The knowledge translation literature uses similar terms in describing the turning of knowledge into action.[3] Often used in association with nursing, medicine, bio-medical engineering research and associated fields, examples of knowledge translation include the application of laboratory discoveries in diagnosis or treatment of disease (new drugs, for instance) and the use of validated procedures, tests and treatments in practice and policy (new clinical administrative procedures). In some of the literature the knowledge-into-action process sounds like the linear model of innovation, involving the "…(a) incorporation of basic science innovations into the design of new tests and treatments, and (b) uptake of validated tests and treatments into clinical practice."[4] Another linear model-like description characterizes the process this way: "Knowledge translation is about turning knowledge into action and encompasses the process of both knowledge creation and knowledge application."[5] Where the idea of a changing research culture can be seen is in the emergence in the alternative characterization of knowledge translation as a process of engagement of knowledge users in research. To distinguish it from "basic" knowledge translation, this user-oriented form is often referred to as integrated knowledge translation (or "iKT"). The emphasis is on "exchange of knowledge between relevant stakeholders that results in action . . ." with a first research step consisting of identification and cultivation of relationships with users based on a common understanding of iKT.[6] As a result, knowledge users are said to collaborate with researchers to determine the research questions, methodology, data collected, as well as interpret findings, and help disseminate research results. Others have noted the similarity of knowledge translation with mode 1 research, and iKT with mode 2, and in particular the situating of research within the context of application from the outset of the project.[7]

Although the mode 2 concept in particular has been strongly criticized as more political ideology than descriptive theory, overstating the role of universities in innovation, and wrongly viewing mode 2 as something new, there are nevertheless strong commonalities with more critical accounts of changes in scientific policy, funding and research over the past fifty years. [8] This includes work by the Paul Forman

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208; H. Etzkowitz and L. Leydesdorff, "The dynamics of innovation: from National Systems and "mode 2" to a triple helix of university–industry–government relations," Research Policy 29, no. 2 (2000): 109–123; H. Etzkowitz, A. Webster, C. Gebhardt, B. Terra, "The future of the university and the university of the future: evolution of ivory tower to entrepreneurial paradigm," Research Policy 29, no. 2 (2000): 313–330.

[2] Laurens K. Hessels and Harro van Lente, "Re-thinking new knowledge production: A literature review and a research agenda," Research Policy 37 (2008): 740–760.

[3] Trisha Greenhalgh and Sietse Wieringa, "Is it time to drop the 'knowledge translation' metaphor? A critical literature review," Journal of the Royal Society of Medicine, 104 (2001): 501–509.

[4] Ibid, 502.

[5] Ian Graham, et al., "Lost in Knowledge Translation: Is it time for a map?" The Journal of Continuing Education in the Health Professions, 21 (2006): 13-24, 22.

[6] Ibid.

[7] Sarah J. Bowen and Ian D. Graham, "From Knowledge Translation to Engaged Scholarship: Promoting Research Relevance and Utilization," Archives of Physical Medicine and Rehabilitation, 94 (1 Suppl 1), (2013): 3-8, 7; M.L. Gagnon, "Moving knowledge to action through dissemination and exchange," Journal of Clinical Epidemiology 64 (2011): 25-31, 28; Myfanwy Morgan et al. "Implementing 'translational' biomedical research: Convergence and divergence among clinical and basic scientists," Social Science & Medicine 73 (2011): 945-952, 951; Alison Kitson, "The need for systems change: reflections on knowledge translation and organizational change." Journal of Advanced Nursing 65 (1), (2009): 217–228, 225; Carole A. Estabrooks, et al. "Knowledge translation and research careers: Mode I and Mode II activity among health researchers," Research Policy 37 (2008): 1066–1078, 1069; Greenhalgh and Wieringa, "Is it time to drop the 'knowledge translation' metaphor?"

[8] Benoit Godin, "Writing performative history: the new new Atlantis?" Social Studies of Science 28 (1998): 465–483; Terry Shinn, "The Triple Helix and New Production of Knowledge: Prepackaged Thinking on Science and Technology," Social Studies of

on the reversal in primacy of science and technology, Phillip Mirowski's Science-Mart, post-normal science, finalisation science, strategic research/strategic science, academic capitalism, and post-academic science. Forman and Mirowski, for instance, share the view that we are living through a profound transformation of science. Both focus on the transition period of the 1980s and the rise of a view of science as an end to technology, a corresponding decline of the idea of science as an end to itself or as an agent to the progress and expansion of an enlightenment culture, and the trend to escalated and enhanced commercialization of science.[9]

In this article we argue that, in contrast to the common view that research in universities and public research institutions has increasingly moved away from basic problems and to commercialization, research in this field has moved in the opposite direction, from design-oriented projects beginning in the 1960s to a focus on long-term research problems, beginning in the 1980s. The paper begins with a brief introduction of the history of powered, upper-limb research in Canada. We then examine the history of research in this field at the Ontario Crippled Children's Centre and the University of New Brunswick. These research groups were chosen as they both emerged as international leaders the field by the 1960s and were two of the few groups world-wide that developed commercial, upper-limb myoelectric limb systems.[10] Following these histories we examine the cases in light of the theories of changing research approaches during the period, draw conclusions as to the forces at work in the cases, and offer suggestions for future research on engineering science during the period.

Background

Canada was a relative latecomer to research on myoelctrically-controlled artificial arms and hands. The origins of the field were in the late eighteenth century discovery of the relationship between electricity and muscle contraction by Luigi Galvani, subsequent work to prove electrical currents did originate in muscles, and then development of instruments in the late nineteenth century and early twentieth centuries to measure electrical currents.[11] Although a bench-top electric prosthetic hand had been demonstrated in Berlin in

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Science 32 (2002): 604; David Mowery and Bhaven Sampat, "Universities in National Innovation Systems," in The Oxford Handbook of Innovation. ed. Jan Fagerberg, David Mowery, and Richard Nelson. (New York: Oxford University Press, 2005), 209-239; Steve Fuller, The governance of science : ideology and the future of the open society (Philadelphia: Open University Press, 1999). He argues the two modes were institutionalized only within a generation of each other, mode 1 by the 1870s and mode 2 by 1900; Philip Mirowski, Science-Mart: Privatizing American Science (Cambridge: Harvard University Press, 2011).

[9] Paul Forman, "The Primacy of Science in Modernity, of Technology in Postmodernity, and of Ideology in the History of Technology," History and Technology, 23, no. 1/2, March/June (2007): 33; Paul Forman, "On the Historical Forms of Knowledge Production and Curation: Modernity Entailed Disciplinarity, Postmodernity Entails Antidisciplinarity," Osiris 27, (2012): 71; Philip Mirowski and Esther-Mirjam Sent, "The Commercialization of Science and the Response of STS," in The Handbook of Science and Technology Studies, 3ed., ed. Edward J. Hackett et al. (Cambridge: MIT Press, 2008), 635-689; J.R. Ravetz, "Usable knowledge, usable ignorance: incomplete science with policy implications," in W.C. Clark and R. C. Munn, ed. Sustainable development of the biosphere (New York: Cambridge University Press, 1986), 415-432; John Turnpenny, Mavis Jones and Irene Lorenzoni, "Where Now for Post-Normal Science?: A Critical Review of its Development, Definitions, and Uses," Science Technology Human Values 36, no. 3 (2011): 287-306; S. Funtowicz and J. Ravetz. "Science for the post-normal age," Futures 25, (1993): 735–755; P. Weingart, "From "Finalization" to "mode 2": Old wine in new bottles?" Social Science Information 36, no. 4, (1997): 591–613; S. Slaughter and L. Leslie, Academic Capitalism: Politics, Policies, and the Entrepreneurial University (Baltimore: The John Hopkins University Press, 1997); J. Ziman, J., Real Science: What it is, and What it Means (Cambridge: Cambridge University Press, 2000),19.

[10] The federal government funded other two units: the Rehabilitation Institute of Montreal and the Rehabilitation Hospital in Winnipeg. The upper limb R&D at the Montreal Rehabilitation Institute was relatively short-lived, and the R&D at Winnipeg focused on lower limb prostheses.

[11] The instruments were: metal surface electrodes to make the measurement of muscle signals by the galvanometer more accessible; the application of the cathode ray tube in 1920 to make possible the amplification of muscle signals detected by the galvanometer; and the introduction of vacuum tube amplifiers in the late to simplify the task of detecting the electromyographic signals, allowing the new art of electromyography to find practical usages in the clinical environment.

1919,[12] the concept of using myoelectric signals in stump muscles for control of a mechanical hand would have to wait a generation until it was first reduced to a proof-of-concept device. The device was developed by Ronald Reiter during his graduate studies in physics at the University of Munich from 1944 to 1948. The system he designed and built was a literal bench-top tool due to its dependence upon A.C. electricity and a vacuum tube amplifier the size of an attaché case. It used a three-state controller and proportional control as devices do today, but never proceeded to clinical investigation.[13] Reiter stated that in 1948, ". . . the political and economic conditions in Germany were not conducive to further work on the project."[14] Although published, the work would only be rediscovered after the initial development of similar myoelectric systems in the 1960s.

In the US, the US National Academy of Sciences discovered near the end of World War II that little modern scientific effort had gone into the development of artificial limbs, and in 1945 initiated a "crash" research program funded by the Veterans Administration Office of Scientific Research and Development. The state-of-the-art devices in 1945 were shoulder powered, artificial limbs for adult arm amputees, using cables (like those used in bicycles today) to open and close the wooden, mechanical hand. For children, it was cable controlled hooks, as artificial hands had not been developed in small sizes.[15] One of the major outcomes from the sponsored programs of the Office of Scientific Research and Development came from a project at International Business Machines Corp. (IBM). IBM investigated the concept of an electric arm, and then developed a device with financial support from the US Veterans Administration.[16] From that project came the realization that users could not control the electric arm without conscious thought, and that for most amputees the level of effort to control a prosthesis exceeded the benefits received. The suggestion was that future research should focus on electric arm control. Although the concept had been demonstrated nearly a decade early in Germany, it was this work that would influence the field to focus on control of artificial arms and hands through myoelectric systems.[17]

As with space rocketry, the most sensational developments of the period occurred in the Soviet Union. The concept of using electrical signals from muscles to control a prosthesis was first formulated in 1957 by a joint group at the Machine Research Institute and the Central Research Institute.[18] At the 1958 World's Fair in Brussels, the USSR's pavilion of new technological breakthroughs showcased the Russian Hand, a myoelectric forearm prosthesis powered by a miniature D.C. motor and battery pack worn on the amputee's belt. The design was to have significant influence in the United Kingdom and Canada, where rights were licensed for manufacturing.[19] Worldwide, it raised expectations about what could be done for amputees and

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[12] G. Schlesinger, R.R. DuBois, R. Radike, and S. Volk "Der mechanische Aufbau der künstlichen Glieder" I.: Der Eratzrarm. In: *Ersatzglieder und Arbeitshilfen für* Kriegsbeschädigte und Unfallverletzte ed. M. Borchardt, K. Hartmann, H. Leymann, R. Radike, G. Schlesinger. Berlin, Germany: Julius Springer-Verlag. (1919).

[13] D.S. Childress and M.V. Podlusky, "Myoelectric control – Letter to the editor," Medical & Biological Engineering 7 no. 3 (1969): 345.

[14] Louise Boldon, A History of Myoelectric Control (MA Thesis, University of New Brunswick, 1983).

[15] US Department of Health, Education and Welfare, Office of Vocational Rehabilitation, Progress in Prosthetics (Washington: US Government Printing Office, 1962), 2.

[16] Samuel W. Alderson, The Electric Arm," in Chapter 13 Klopsteg and Wilson Ed. Human Limbs and Their Substitutes (New York: McGraw-Hill, 1954).

[17] The word "myoelectric" combines the Greek word "myo," meaning muscle, with "electric." It is, in brief, electricity from muscles. R. N. Scott defined an analog upper limb myoelectric prosthesis as follows: "The concept of a myoelectric prosthesis is simple. The electrical activity naturally generated by contracting a muscle in a residual limb is amplified, processed and used to control the flow of electricity from a battery to a motor, which operates an artificial limb." See: L. McLean and R. N. Scott, "The Early History of Myoelectric Control of Prosthetic Limbs (1945-1970)" in Powered upper limb prostheses: control, implementation and clinical application, ed. Ashok Muzumdar (Berlin: Springer Verlag, 2004), 1.

[18] B. Popov, "The Bio-Electrically Controlled Prosthesis," J. Bone & Joint Surg., 47B (1965): 3.

[19] In 1964, personnel from the Rehabilitation Institute of Montreal travelled to the Central Institute for Prosthetics and Prosthetic Development in Moscow and licensed the Canadian manufacturing rights to the Russian myoelectric arm. Expectations were greater than realities, although there were resulting clinical products developed from the Russian Hand licensing deal. See: E.

provided fuel for scholarly and popular science articles on the future of the man-machine interface and the field of cybernetics.

In Canada research on artificial hands and prostheses began in a hospital: in 1949 at the Sunnybrook in Toronto, which was the laboratory facility of Canada's Department of Veterans Affairs. In the 1950s, the focus was on making existing body-powered and mechanical-hand prostheses more useful through the use of new plastics and materials, novel suction socket fittings, and cosmetic gloves. The development of powered hands in Canada began in response to a funding program created as a result of the prescription sale of thalidomide from April 1, 1961 to March 2, 1962.[20] In 1962, the Department of National Health and Welfare convened an expert committee on the rehabilitation of congenital anomalies associated with thalidomide.[21] The committee reported and made recommendations for research and training. The department took action. Starting in 1963 the department provided $200,000 annually for three research and training units at the Rehabilitation Institute of Montreal, the Rehabilitation Hospital in Winnipeg and the OCCC.[22] A fourth, at the UNB, was added later that year. The Rehabilitation Institute of Montreal focused its efforts on improvement of the Russian Hand, which it had in-licensed to exploit within Canada. The Rehabilitation Hospital in Winnipeg did work on lower-limb prosthetics.

University of New Brunswick's Institute of Biomedical Engineering

UNB's Institute of Biomedical Engineering (IBME) owes its existence to a request for assistance in 1961 from a local rehabilitation centre aware of work at UCLA on new prosthetic devices for quadriplegic patients. One of the UNB faculty members who attended the meeting convened by the dean of science was a young assistant professor of electrical engineering named Robert N. Scott.

Scott began his bachelor of science degree at UNB in 1950, graduating with twelve other electrical engineers in 1955. According to Scott, education in electrical engineering at the time was mostly practical, with very little theory in the curriculum. There were no electives outside of the eight courses per term. The curriculum did not yet include solid-state electronics or computer/digital systems. Control systems theory was in its infancy. The education of undergraduate electrical engineering students was still largely grounded in the craft tradition of engineering, not the applied science practice model emanating from US institutions like MIT and being transferred north via Canadian universities like the University of Toronto. For example, at the start of his studies, Scott was instructed to bring a good pair of pliers and an electrician's knife to his courses.

Scott joined the electrical engineering department as a faculty member in 1959. At that time no one in the department had a doctoral degree. There were two faculty members with masters degrees, but, according to Scott, these were almost honorary, based on teaching experience and one paper. The faculty focus was on teaching, not research. However, the dean of UNB engineering, a recipient of a master of science degree in electrical engineering, saw the way the future was going and encouraged Scott to do research, even though it would not be easy with the lack of mentors and meagre equipment and budgets in the electrical engineering department.

The result of the meeting with the local rehabilitation centre was the provision of technical assistance to quadriplegic patients to improve control of their wheel chairs. It also led to the formation of a new group, called "The Technical Assistance and Research Group for Physical Rehabilitation (TARGPR)." The idea that emerged from discussions with the patients and centre representatives was to address a communication and control problem between the person and the wheel chair. Scott contacted the researchers at UCLA who

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Sherman, G. Gingras, A.L. Lippay, "New trends in externally powered upper extremity prostheses," World Medical Journal 15, no. 5 (September-October, 1968): 121-125.

[20] By September 1964 the Department had identified 82 children affected by thalidomide, with most in Ontario and Quebec.

[21] Among the ten clinical experts on the committee were Dr. John Hall from the Ontario Crippled Children's Center and Dr. Gustav Gingras from the Rehabilitation Institute of Montreal. The Report of the Expert Committee of the Habilitation of Congenital Anomalies Associated with Thalidomide, dated December 1962, was obtained under an access to information request.

[22] The grant was continued until March 31, 1975, three years after the termination date of March 31, 1972.

were building a powered splint that was controlled by a tongue-operated switch. Users were able to feed themselves with the tongue-controlled arm. This was the seed of the idea–that muscles could be used to control a device that would influence Scott and the Institute throughout its history. For the two patients at the local rehabilitation centre, Scott built a tongue-operated controller for their electric wheel-chairs.

The group decided to focus on myoelectric controls as it seemed the most promising technology. Of the technical program that developed Scott said: "We initially defined the objectives in terms of the clinical education, and not in terms of academically respectable research. We did not try not to do good science. We were not at this very long before we needed research to support the application we were working on."[23] It was far from curiosity driven research, even for engineers, so much so that when the groups received initial funding from the Department of National Health and Welfare, the first thing was not to hire graduate students, but professional technical staff. It was only afterwards that Scott realized that he could develop research topics that could be undertaken by graduate students.

The first graduate student to fill this role was Philip Parker, originally an electrical engineering graduate student of Scott's in the early 1960s, and subsequently a faculty member for twenty-nine years in UNB's department of electrical engineering. Both were interested in research to assist in developing a system to meet clinical requirements. Scott directed the Institute. He and one of the Institute's professional staff designed the control system. Parker developed the algorithms to control the switching levels among limb functions. Parker was its research leader, with a focus on understanding the human neuromuscular system and control of prosthetics limbs. Instead of importing systems from elsewhere to produce makeshift solutions, such as hardware from UCLA to make a tongue-controlled wheelchair, UNB now had the people to develop conceptual designs and implement them in engineered systems.

It was a transitional period at UNB's faculty of engineering. Parker obtained his doctoral degree from UNB under the tutelage of Scott, the director of graduate studies in the department and recipient of a mere bachelor of science degree. In 1965, the informal, unincorporated and unaffiliated technical assistance and research group for physical rehabilitation (TARGPR, which, uncharacteristically of the age, emphasized technical assistance ahead of research), was constituted a UNB research institute by the senate and board of governors to undertake interdisciplinary research involving more than one faculty. Named the Bioengineering Institute,[24] it was given a three-fold mandate that mirrored that of the university: teaching, research, and community service. The applied science model of engineering had come to UNB, as it had at many Canadian and US engineering schools in the 1960s.[25]

One of UNB's major contributions to the advancement of myoelectric hand technology was in signal processing. A challenge in developing systems in the 1960s was in producing a prosthetic device design that was the right size and shape to match the lost limb, and to avoid bumps and bulges in accommodating the electronics. The importance of this concept came from collaborations with U of T. Throughout the early and mid-1960s UNB was committed to the idea of prosthetics as primarily functional devices, the equivalent of "pliers on wires."[26] John Hall, head of pediatric orthopaedics at the University of Toronto, introduced the UNB group in 1968 to a fifteen-year-old girl missing a limb below the elbow. She was highly functional with her prosthesis. She had been wearing a conventional prosthesis held on with a harness strap. Although she was agreeable with a trial of an electric powered hand, in the fitting she said she wanted Hall "to take that damn thing away from me." It did not look good or fit. The message from Hall and the patient was that they wanted something comfortable, good looking, and last, but not least, functional. The UNB group had been focused on making an electric pair of pliers work better, such as the system in Figure 1.

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[23] R.N. Scott, author interview, May 5, 2010.

[24] Subsequently it was re-named the Institute of Biomedical Engineering,

[25] In some engineering departments at UNB, such as surveying and chemical engineering, it was there at the outset in 1960. One of the sources of influence for the applied science model of engineering research were the conferences organized by the U.S. National Academy of Sciences Center for Prosthetics Research and Development (CPRD) in 1961, 1963 and 1965. At these UNB faculty learned about its model of research, development, testing and evaluation of new prosthetic devices.

[26] R.N. Scott, author interview, May 5, 2010.

That was a turning point for Scott. UNB's focus would have to change to listening to the patient, and fitting the technology to the requirements of a comfortable and attractive prosthesis.[27]

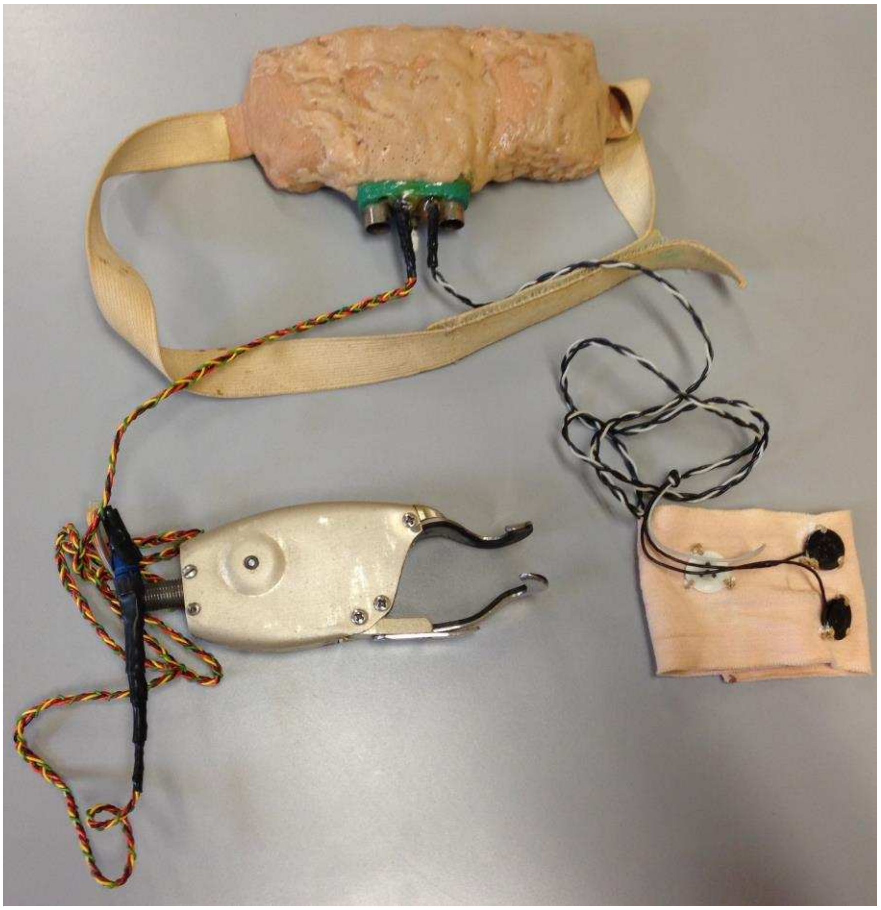

Figure 1: UNB myoelectric control system, 1965, including controller with strap (top), terminal device (left) and electrodes (right). Source: David Foord

This allowed the Bioengineering Institute and the OCCC to get ahead of other research groups in the development of myoelectric controls for integration in a natural looking and comfortable prosthetic device. In other words, the electronics and myoelectric controls would be built into the arm as illustrated in Figure 2, not worn outside the prosthesis. A second novel feature of the UNB myoelectric controls was that it was not a highly intelligent device requiring minimal input from the user. The UNB group found that this design faced a psychological issue for patients. They did not get the same sense of satisfaction from a device that was highly automated (i.e. a device that responded to the command "feed me" by moving the arm and hand in a pre-programmed pattern to lift a spoon to a mouth). Scott recalled that quadriplegic patients at the local rehabilitation centre wanted a wheelchair they could drive, and did not want to be driven or pushed. For Scott it was about the feeling of being in control.[28]

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[27] Patients were primarily children given the focus of the Department of National Health and Welfare funding. Unlike research at MIT and US rehabilitation research centres, the focus at UNB during the 1960s and 1970s was not on veterans.

[28] R.N. Scott. author interview, May 5, 2010.

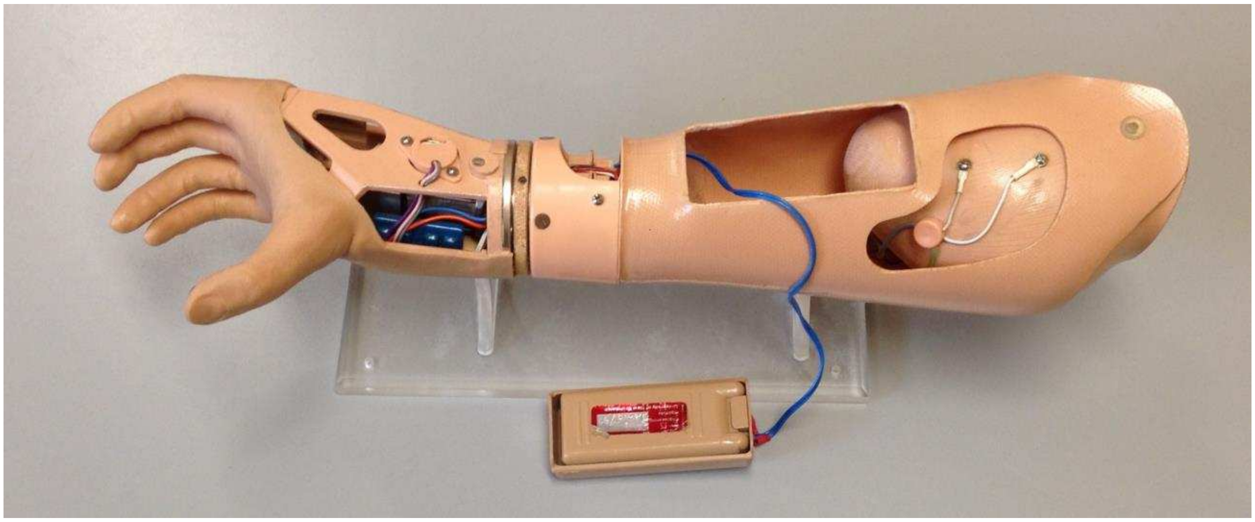

Figure 2: Adult prosthesis with UNB control unit, circa 1977. Source: David Foord.

In 1981 the Institute developed a regional limb fitting clinic and service, a myoelectric controls manufacturing group and a distribution group. The concept behind the manufacturing and distribution business was that it would make and sell products developed by Institute researchers as well as distribute products in Canada for firms such as Liberating Technologies Inc. in the US and RSL Steeper in the UK, with profits distributed back to the Institute to further the research agenda. Mark-ups on the cost of production of UNB-based products were modest. For example, in 1980 a myoelectric trainer that had a cost of production of $3,300 was sold for $3,500.[29] It was a novel and unconventional approach. The convention was (and still is) for universities not to sell biomedical products, but rather to license technology to firms that can afford the cost of commercial or clinical product development and accept the liabilities that go along with product sales and service. However, with the exception of a handful of mostly US institutions such as MIT and the University of Wisconsin, these were still early days for university technology transfer and new product development. The Bayh-Dole Act had been passed, but the creation and staffing of technology transfer was just getting started.

This experiment in business lasted about eight years. The fitting service and manufacturing and distributions groups lost money due to small mark ups on products and low sales numbers. In the biggest sales year, twenty-two systems were sold. In 1989, the business was wound up and rights to the locally manufactured products were sold to Liberating Technologies Inc. This meant that some Institute technology found application in Liberating Technologies Inc. products, whereas others, such as the UNB wrist controls, were shelved. With the wind-up of his operation, the Institute brought back the fitting service to its campus location.

By the early 1990s Scott had retired a new generation of Institute researchers, trained under Parker, were rising in prominence in the field, including two future directors of the Institute, Bernie Hudgins and Kevin Englehart. This solidified the transition of the Institute to a research orientation. The specific research focus was on the application of pattern recognition for control of myoelectric prostheses for persons with a loss above the elbow, a group that had not been well served by first generation of myoelectric controlled artificial arms that had emerged into commercial use by the late 1970s. This presented a more challenging research

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[29] Ibid.

area than one oriented to the design of control systems and hardware for below elbow amputees, which could use signals from two or more muscles.

The research rationale for signal or pattern recognition methods was that the most common functions of the elbow or hand occur from the work of groups of muscles, only some of which directly control the movement. For instance, when the elbow brings the forearm from beside the leg to the chest (as when lifting a dumbbell), there is also movement of muscles in the shoulder blade. Those back muscles do not control the movement, but rather fix and stabilize the arm so other muscles can exercise direct control. This means that the myoelectric signals are not simply a single pulse of electricity from a bicep or tricep muscle, but a complex pattern of signals.

For upper limb prosthesis myoelectrics, pattern recognition offered the possibility to recognize the patterns in myoelectric signals from specific movements such as "open hand" and "close hand." When the operator sent a command to close the hand, the microprocessor analyzed the new data against a model based on previous signal information. If the computer recognized that this particular signal was similar to previous ones used to close the hand, the controller then selected a pre-programmed movement: close hand. UNB's IBME emerged as a leader in pattern recognition and in turn from exploring ways to make the most of information from surface electrodes to making sense of information directly from the nerves. As part of his doctoral research in the late 1980s and early 1990s, Bernie Hudgins discovered a "motor plan" in the myoelectric signals accompanying the onset of arm or hand movement.[30] His thesis was that motor plans were the outcome of learning simple, ballistic contractions, which, once a movement had been learned, became stable for a given task. It is like artillery pre-planned or "predicted fire" plans in that the muscles in the arm and hands are also trained and then set to fire according to specific and detailed sequences. Second, it is only with great difficulty that this motor plan could be discerned by second order information, such as the sound of gunfire or neuromuscular signals picked up form an electrode on the skin. It was these difficulties that opened up research issues in the application of pattern recognition in order to understand the by-product of complex temporal and spatial muscular signals.

According to Englehart, what had occurred was a change from "a very use oriented field, focused on how to make prosthesis work in the 1960s, to interest in the 1970s in the concept of a "man-machine interface," and in the late 1970s a focus on commercialization of devices and use-oriented application of EMG signal processing."[31] And then, according to Englehart, advances in myoelectric controls sort of died for fifteen years with no fundamental change. What brought the field out of this lacuna was Hudgins's dissertation in 1991, which created an interest in the application of pattern recognition to EMG control, and was followed by hundreds of papers written thereafter.[32] For Englehart, it was here that he saw a role and potential for science. The relevant questions were how to make it work and how to measure it to improve the user experience. Englehart's own work built on Hudgins's to develop a language for using pattern recognition in the field, and a series of papers he published in the 1990s demonstrated that it could be done with modest computer systems with low-power requirements.

Parker, Englehart, and Hudgins research on the challenge of extracting information from muscle-group activity to control multifunction prostheses continued through the 1990s with support from various research funding bodies. Funding from the Natural Sciences and Engineering Research Council was a staple, increasingly supplemented in the late 1990s and 2000s by new innovation funding programs, and funding to support international collaborations as the Institute's signals processing capabilities gained recognition. Interestingly, even as the funding began to call for commercialization and new development engineer

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[30] B.S. Hudgins, P. Parker, and R.N. Scott: "A new strategy for multifunction myoelectric control," IEEE Transactions on Biomedical Engineering, 40, no. 1 (1993): 82-94; B.S. Hudgins, "A Novel Approach to Multifunction Myoelectric Control of Prostheses," Ph.D. Thesis, Department of Electrical Engineering, University of New Brunswick (Fredericton, University of New Brunswick: 1991).

[31] K. Engelhart, author interview, April 23, 2010.

[32] The paper based on the dissertation has been cited 911 times, according to Google Scholar on August 3, 2015. See: B. Hudgins, P. Parker, R.N. Scott, "A new strategy for multifunction myoelectric control" IEEE Transactions on Biomedical Engineering. 40, Issue 1, (1993), 82-94.

positions in funding proposals (instead of the research engineers that had been fixtures in the 1990s), the Institute's researchers—although open to commercialization of their research—continued to persevere in their niche of control methodologies. Although they had long ago reversed the priority of design and research that was inherent in the title of the original "Technical Assistance and Research Group for Physical Rehabilitation," that had continued an ethic of focusing on poorly served patients groups (previously, below-elbow amputees, now above-elbow) and development of systems that were relatively low-cost.

In summary, there were two UNB cases: one design-engineering case, and a second focused on pattern recognition scientific research that began to move into clinical application by the early 2000s. The original group reflected the craft approach to engineering design, beginning with need, not research. Technical assistance came first, and was subservient to ends of physical rehabilitation. This was the case with the assistance to quadriplegic patients to improve control of their wheel chairs, as well as the collaborative design work with the OCCC. Systems were defined, developed, tested and improved in the clinic, not in the laboratory, in discussion with occupational therapists, prosthetists, production managers, and design engineers. Research was a means to the end of technical assistance, and was acquired only when it was discovered that issues could not be solved with existing knowledge. The second case saw the rise of a scientific research culture within electrical engineering at UNB that grew as the craft tradition withered. It more closely aligned with the "scientific discovery" approach to development, internally driven by autonomous, university and discipline-based researchers, although it also shared mode 2 characteristics such as being subject to multiple accountabilities.

As to the forces behind UNB's work in myoelectric controls, the list must include the federal government funding programs in Canada and the U.S. (which, in the case of the U.S., resulted in selection of myoelectric control systems for powered upper limb devices), collaboration with colleagues in universities, hospitals and clinics, users, and technological advancement in battery, computing and materials. Technological innovation was connected to patient influence. Lighter, more efficient batteries and materials allowed prosthetists to design and fit hands for younger children. In turn, they learned that children who got their first prosthesis at 12-15 months used it more spontaneously. They wanted "broken arms" fixed more quickly because they were highly dependent on it. This led to more refined controls systems. Faculty and staff also exercised power in these cases, for example in using applied research and innovation oriented funding programs to persevere in addressing complex research problems to serve user groups. Last, and not to be missed, were the changing practices and identities of engineers. Although a transition from emphasis on design to training in mathematics and sciences had been underway since the introduction of engineering programs in Canadian and U.S. universities in the 1860s and 1870s, and the resolution of the "shop culture" / "school culture" conflict in the 1880s and 1890s with a degree-structure that combined both science and mathematics courses with design instruction and projects,[33] the spread of the applied model occurred much later. According to Bruce Seely, most American engineering colleges first fully embraced an analytical mode of engineering science immediately after World War II. At UNB's department of electrical engineering this influence began in the 1960s, but was not fully embraced until faculty members trained in the engineering design tradition had retired.[34]

Ontario Crippled Children's Centre

The Ontario Crippled Children's Centre's (OCCC's), established in 1957 and now called Holland Bloorview Kids Rehabilitation Hospital, was from the early 1960s to the early 1990s a pioneer in the development of myoelectrically controlled hands, wrists, and elbows for children. These new prostheses, illustrated below, were created by an interdisciplinary team of researchers, occupational therapists, electrical engineers, mechanical engineers, and product managers from the Centre, UNB, and a local technology transfer company, Variety Ability Systems Inc. (VASI). The early years, from the 1960s to the

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[33] Eugene Ferguson, Engineering and the *Mind's* Eye (Cambridge: MIT Press, 1991), 1.

[34] Bruce Seely, "The Other Re-engineering of Engineering Education, 1900–1965," Journal of Engineering Education, (July 1999): 285-294.

mid-1970s, saw the creation of the technologies and institutional structures that would underlay the development of VASI's commercial products. The coming together of the interdisciplinary team and development of these legacy products occurred during the middle period, from the late 1970s to the early 1990s. By the late 1990s the novel development activities had begun to wind down, although VASI's production business continued throughout the decade until 2005, when it was acquired by the German prosthetic device manufacturer, Otto Bock.

The origins of the OCCC's involvement in the research and development of myoelectric upper limbs was in its selection as one of the four PRTUs. In 1964 the OCCC had 600 children registered with its PRTU clinic. Twenty-one of those children were born to mothers who had taken the drug thalidomide while pregnant.[35] The approach the OCCC planned for development was the conventional engineering model of design-build-test, and repeat.[36] Hooks, wrists, hands, elbows and shoulder units were designed and built, tested in the laboratory, and then applied to amputees. VASI hands and elbow are illustrated in figures 3 and 4.

Figure 3: VASI electric hands for children aged 0 to 11 years produced from 1984 to 1987. Source: David Foord

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[35] W. Sauter, "The use of electric elbows in the rehabilitation of children with upper limb deficiencies," Prosthetics and Orthotics International, 15 (1991): 993.

[36] Ontario Crippled Children's Centre. Annual Report, October 15, 1964 (Toronto: Ontario Crippled Children's Centre, 1964), 14.

Figure 4: VASI electric elbow for children produced from 1984 to 1987. Source: David Foord

In addition to the influence from the National Health Grant, there was technical guidance from the Center for Prosthetics Research and Development (CPRD) in the United States, and conceptual influence from the existence and design of the Russian Arm. The CPRD's recommendation that the hook and other electric devices should use a twelve-volt power supply was followed by the OCCC. The influence from the Russian Hand occurred indirectly. Unaware of Ronald Reiter's work in Germany, lessons from the Russian Hand suggested that a clinically useful myoelectric arm could be designed and manufactured. For the Toronto PRTU in the 1960s, the primary point of comparison was with the Russian Hand, and, in particular, its weight, which was deemed too heavy, and motor torque (or force) that was found to be too weak. Initial success for the Toronto group was to build and test a hook powered by a twelve-volt battery that weighed less and had twice the torque of the Russian Hand.[37]

The OCCC staff knew from the beginning that a critical element of any electric hand was the myoelectric control system. As a result, they monitored developments at other research centres on control systems, including electromyography or EMG systems under development in Russia, by Bottomley in the UK, Scott at UNB, and at UCLA and Philco. By 1965 OCCC had concluded that the UNB myoelectric system showed enough promise to use in their program, and Scott was brought in as its electronics consultant.[38]

In 1967 twelve child-sized electric elbows had been developed by the Toronto PRTU and fitted to a variety of patients. They were found to be "particularly acceptable," with the most common complaints being noise,

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[37] Ibid, 6. The Toronto group used ten nickel-cadmium button cell type batteries to achieve twelve volt supply.

[38] Ontario Crippled Children's Centre. Annual Report, 1965 (Toronto: Ontario Crippled Children's Centre, 1965).

wire breaking, and occasional clutch slipping. The problem of masking gear noise was identified as one of the major improvements to be undertaken in 1968.[39] Five different types of controls were used on these elbows, one of them being the UNB myoelectric controller. By late 1967 the OCCC had, on the basis of these fittings and testing, developed plans for production engineering, manufacturing, distribution and servicing.[40]

Production began in 1970 at a 3,600-square-foot facility in Toronto. It was organized by the Variety Club of Toronto, a chapter of an international charitable organization headquartered in Pittsburgh. Established in 1948, the Toronto chapter operated a vocational training school for boys with physical handicaps. This new production facility was intended to be something quite different. The system that emerged was one in which the OCCC's PRTU researched, developed, designed and tested prosthetics devices,[41] the Variety Club of Toronto manufactured prosthetic devices, and the OCCC's prosthetic service delivery program performed the fittings. None of these relationships were exclusive. The OCCC licensed its devices to Liberty Mutual in the United States. The Variety Club manufactured the North Electric hand developed by Northern Electric Corporation (subsequently, Nortel). The OCCC fit devices made by Otto Bock. The name of the OCCC would change over the years, but the system endured.[42]

As with UNB, the loss of funding from the Department of Health in 1975 was a major event for the OCCC. But unlike UNB, it did not mark the beginning of a transition to a research culture. In part, this was a function of an institutionalization of interdisciplinary activities within a clinic. Projects had weekly meetings involving therapists, prosthetists, VASI representatives, and researchers. According to the director of the rehabilitation group, Mickey Milner, "Continuity had built up by this point. Everyone was on the same page."[43] OCCC occupational therapist Hubbard concurred.[44] She confirmed the bi-weekly meetings included researchers, clinicians, occupational therapists, prosthetists, engineers, and VASI representatives. It was a forum for discussing what clinical ideas might be taken into research, and what clinical designs could be transferred to VASI for production. According to the 1987 OCCC annual report: "Close proximity of the clinical service to the design process promotes ongoing interactions between engineering and clinical staff and communication with children and their families. This aids in understanding users' needs and expectations while examining the developmental feasibility in terms of a practical outcomes."[45]

However, this collaborative and interdisciplinary approach did not last. Milner said the pressure to publish research results increased as the discipline of engineering became more research intensive, and as the availability of research funding increased. "These people wanted to establish their careers," Milner said.[46] This meant the researchers focused more on research projects that would generate publications and not necessarily clinical outcomes. The OCCC occupational therapist Sheila Hubbard agreed. She said this collaborative and interdisciplinary approach lasted for about fifteen years from the late 1970s to the early 1990s. Among the reasons for the change, she cited the formation of a new research institute, creating both physical and intangible distances between the clinics and research, the loss of regular attendance by the VASI personnel, and the change in the Centre's myoelectric provider. Hubbard said: "UNB in the early

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[39] Ontario Crippled Children's Centre. Annual Report, 1967 (Toronto: Ontario Crippled Children's Centre, 1967), 2.

[40] Ibid, 12.

[41] Sauter, "The use of electric elbows," 93.

[42] The 1972-73 OCCC Rehabilitation Engineering report stated: "The child size electric elbow, developed at this centre and the Northern Electric hand are two items that are now manufactured and distributed through Variety Village Electro Limb Centre independent of this research program." Ontario Crippled Children's Centre. Annual Report, 1973 (Toronto: Ontario Crippled Children's Centre, 1973), 7. The PRTU of the OCCC would become the "Powered Upper Extremity Prosthetic Research and Development Programme of The Hugh MacMillan Medical Centre." The Variety Club incorporated a subsidiary corporation called the "Variety Ability Systems Incorporated" or VASI which would subsequently be acquired by Otto Bock.

[43] Ibid.

[44] S. Hubbard, author interview, April 22, 2010.

[45] Hugh MacMillan Medical Centre, Annual Report, 1987 (Toronto: Hugh MacMillan Medical Centre, 1987).

[46] M. Milner, author interview, June 25, 2010.

days was both a clinical collaborator and control system supplier. The UNB system was replaced by Otto Bock. Otto Bock was a supplier to the hospital." Otto Bock did not, however, replace UNB as a product development collaborator.[47]

The outcome of all this collaborative and interdisciplinary interaction was the extension of myoelectric devices to infants. One of the important outcomes was the development of a miniature circuit to permit one-muscle, voluntary opening control of infant electric hands. In Hubbard's words it "revolutionized" their approach, allowing for fittings and trainings to ten months of age, instead of three years, and increasing the odds that myoelectric devices would be permanently used.[48] Hubbard commented that if the child was fitted early the prosthesis became part of them. If fitted later it was simply a tool.[49] The outcome of this "little r & capital D" work, as one VASI staffer called it, and the fittings at OCCC of new prosthetic products to young children, was that commercial companies (which, unlike VASI, were not controlled by clinical organizations) were drawn into developing their own prosthetic products for children

Although during the 1990s and early 2000s VASI continued to develop, improve, and sell upper limb prosthetic products, it was no longer building novel products to prove that myoelectric upper limb prosthetics could be used by infants and children, nor did it have the same kind of contributions from the Bloorview Centre. As a result the fortunes of VASI began to change. Milner proposed the idea of selling VASI. In 2005 the Centre found its buyer, Otto Bock.

In summary, the development process followed by the OCCC was centred on interdisciplinary meetings that identified user needs and the development of designs to address those needs. Prostheses were produced at the machine shop, then tested in user trials. The need for corrections or modifications was identified in the trials and team meetings, and then the process would be repeated. A workable design might be developed within eighteen months, presuming no breakdowns. The next step was to release the design for production. Product developers worked closely with production to do the molding of the prostheses and product tweaks as VASI contracted for parts and prepared its assembly process and marketing plans. Trial and error, not modeling based on theory, informed the group's design activities.

As with the UNB history, there appears to be a reversal of the mode 1-mode 2 narrative, with a kind of mode 2 development from the 1970s to early 1990s 1980s, and then a greater emphasis on scientific research in the 1990s, although not a pure form of mode 1 research. In the first period there was a laboratory-based generation of problems and methodologies, and dissemination of results in hospitals and clinics. The work was trans-disciplinary in the use of trial and error, instead of discipline-based theories and methods being used to solve problems. As well, R&D changed in the earlier period from being the sole domain of electrical engineers to involving occupational therapists, users, company managers, and others involving their own theories, methods, experience, and tacit knowledge to solve problems. There was "speaking back to science" from amputees at the clinic to the occupational therapists and then to the researchers in the biweekly meetings. The "novel forms of quality control" occurred, in part, through the meetings with representatives from product manufacturers, designers, and occupational therapists.

As with UNB, the influence came through the implementation of ideas in public policies and funding programs, initially the ministry of national health and welfare grants for clinical and research activities, then through the Medical Research Council and NSERC funding programs, and then later through innovation funding investments. There were commonalities on the goals of the programs, but also significant differences. The ministry of national health and welfare funding brought researchers into the clinic and hospital, face-to-face with patients. The research council funding required knowledge of the current scholarly literature and a grounding of the project's hypothesis in that work. Although the actors come to the fore in the fine-grained case history, it's the location of interdisciplinary work at the Centre that seems most central to the development of the novel VASI arms and hands for children. The collaborative, user-oriented approach to development was of course critical, but it seems that only in this

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[47] S. Hubbard, author interview, April 22, 2010.

[48] Ibid.

[49] S.Hubbard, author interview, February 24, 2015.

setting could there occur a half century of development and improvement in what became the VASI hands and arms.

Conclusion

In contrast to the view that research in universities and public research institutions has increasingly moved away from basic problems to knowledge production, research in powered-artificial arms in Canada has moved in the opposite direction for most of the period of this study, towards challenging and long-term research problems.[50] The forces behind the earlier design-oriented work included a consulting engineering approach to projects that for many universities pre-dated the applied-science model. This approach exploited the prior research in the Soviet Union and the United States that had selected electric-power and upper-limb myoeletric signals as the preferred means to control the electronic hands, elbows and wrists. The location of the projects within the OCCC was also an important factor in the continued use of the design engineering approach, even after the Department of National Health and Welfare funding program expired. The location of the work opened up the project to other professionals and users not commonly found in university engineering laboratories. The transition to a focus on long-term research problems came with the influence of the applied science model of research, and corresponding growth in university graduate education, engineering research funding programs, and the will of faculty members to orient their projects to address both their perception of the needs of users as well as their interests as researchers. Given the recent design of prosthetic products that incorporate pattern recognition systems, there has recently been been another move to clinically-based development projects, reflecting a situation, which others have observed, where no single view of biomedical science has undisputed authority and legitimacy.[51]

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[50] However, no pure form of mode 1 type research was found in any of our cases. After a generation of research, pattern recognition technology has recently been introduced into commercial product testing.

[51] Myfanwy Morgan et al. “Implementing ‘translational’ biomedical research.” The observation is also consistent with the consensus that emerged in the aftermath of the famous technology push-pull debates framed by projects HINDSIGHT and TRACES in the 1960s, moving from polarized debates to recognition of the co-existence of and differing roles of science-based and application oriented research. C.W. Sherwin and R.S. Isenson, “Project HINDSIGHT,” Science 156 (1967): 1577. Technology in retrospect and critical events in science (Project TRACES), Report, Illinois Institute of Technology (IIT) – National Science Foundation. (Chicago, Illinois: Illinois Institute of Technology, 1968).