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Knowledge Translation in Rehabilitation Engineering Research and Development: A Knowledge Ecosystem Framework

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Abstract

Rehabilitation engineering is concerned with technology innovations and technology-mediated treatments for the improvement of quality of care and quality of life of individuals with disability. Unlike many other fields of health research, the knowledge translation (KT) cycle of rehabilitation engineering research and development (R&D) is often considered incomplete until a technology product or technology-facilitated therapy is available to target clientele. As such, the KT journey of rehabilitation engineering R&D is extremely challenging, necessarily involving knowledge exchange among numerous players across multiple sectors. In this article, we draw on recent literature about the knowledge trichotomy in technology-based rehabilitation R&D and propose a knowledge ecosystem to frame the rehabilitation engineering KT process from need to product. Identifying the principal process of the ecosystem as one of knowledge flow, we elucidate the roles of repository and networked knowledge, identify key consumers and producers in a trinity of communities of practice, and draw on knowledge management literature to describe different knowledge flows. The article concludes with instantiations of this knowledge ecosystem for 2 local rehabilitation engineering research-development-commercialization endeavors.

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> "Talk about those subjects you have had long in your mind, and listen to what others say about subjects you have studied but recently. Knowledge and timber shouldn't be much used till they are seasoned."[1(p118)]

This excerpt from Holmes' most enduring work[1] some 150 years ago succinctly captures several key aspects of knowledge translation (KT) in rehabilitation engineering research and development (R&D). The first sentence suggests a sharing of knowledge among different but equally valued knowledge producers, each with the capacity to provide seasoned knowledge but also to assimilate new knowledge. The second sentence resonates with the knowledge creation funnel in the knowledge-to-action model,[2] where knowledge is increasingly refined before it can be applied. Particularly, in rehabilitation engineering R&D, knowledge is iteratively distilled as it metamorphoses from scientific discovery to proof-of-concept prototype to, ultimately, a functional product that fulfills a particular need.[3]

In this article, we will discuss KT in the rehabilitation engineering R&D context. We first describe the KT challenges facing the rehabilitation engineering discipline. Subsequently, we propose a knowledge ecosystem as one way to understand the KT activities required to go from an identified need to a commercial product. We identify ecosystem inputs and outputs, key consumers and producers, and introduce repository and networked knowledge along with knowledge flows within communities of practice as key constituents of the ecosystem. Finally, we apply this framework to describe KT activities of 2 rehabilitation engineering research, development, and commercialization endeavors.

Rehabilitation engineering R&D

Definitions

The American Code of Federal Regulation (34 CFR 361.5(b)(44))[4] defines rehabilitation engineering as the "systematic application of

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engineering sciences to design, develop, adapt, test, evaluate, apply and distribute technologic solutions to problems confronted by individuals with disabilities in functional areas, such as mobility, communications, hearing, vision, and cognition, and in activities associated with employment, independent living, education, and integration into the community."(p273) Key to this definition is that the application of engineering is predicated by an identified need in a functional area. Assistive technology devices, the technologic solution that fulfills the need, are thus often viewed as the product of rehabilitation engineering activities.[5] According to American public law, assistive technology is "any item, piece of equipment or product system whether acquired commercially on the shelf, modified, or customized that is used to increase or improve functional capabilities of individuals with disabilities" (Technology Related Assistance for Individuals with Disabilities Act, 1998).[6] This definition encompasses the spectrum of advanced body-machine interfaces (eg, neuroprostheses, brain-computer interfaces), electronic (eg, voice-output communication aids), mechatronic (eg, robotics), and mechanical (eg, rollator) devices that are used today to restore or augment function. Traditionally, this definition excludes surgically implanted devices.

In light of these definitions and recent developments in the field, rehabilitation engineering R&D can thus be broadly considered to be any systematic inquiry or investigation concerning the creation, evaluation, and deployment of devices, instruments, technology-mediated interventions or assessments, and health care technologies or systems, whose main goal is to improve the quality of life and quality of care of individuals with disabilities. In the vernacular of the *International Classification of Functioning, Disability and Health*,[7] rehabilitation engineering R&D ultimately endeavors to improve the participation of individuals with disabilities in life activities by providing products, technology, and associated therapies as environmental facilitators (eg, access technologies) and agents that promote functional gains through the modulation of body functions and structures (eg, neuromodulation or functional electrical stimulation [FES]).

KT challenges

KT is the convergence of research (creation of knowledge) and action (the application of knowledge) to ultimately benefit human society.[8] The core principles of KT can be described as: (1) a robust, contextualized knowledge base; (2) continuous dialogue and exchange between researchers and knowledge users; and (3) the capacity to create and respond to KT opportunities.[9] In many areas of health sciences research, successful KT means the exploitation of research evidence in the adoption of new practices or evolution of existing ones, making decisions or taking action, or influencing the direction of future research.[10] In addition to the above KT activities in health research, a key indication of successful knowledge uptake in rehabilitation engineering is the adoption and implementation of a technology-based solution by a target user or user group. The KT cycle in rehabilitation engineering R&D is often regarded as incomplete until an evidence-informed product is available, used by customers, and is supported in terms of customer service and the jurisdictional assistive device funding structure. As such, the KT process in rehabilitation engineering necessarily entails the exchange, synthesis, and application of not only discovery-based knowledge, but also technology development knowledge and device production knowledge.

While the lag between evidence generation and implementation is estimated to be 20 years in some areas of health research,[11] the adoption of rehabilitation technology must be achieved with greater immediacy. Given the exponential rate of technologic evolution,[12] the rehabilitation technology itself, its computing platform (if applicable), or other key components risk obsolescence if not translated in an expeditious manner. Thus, in many respects, the fruits of rehabilitation engineering R&D may inherently bear an expiry date.

In rehabilitation engineering, unsuccessful KT can be considered an "innovation implementation failure,"[13] which is the "failure of an innovation to achieve the gains expected by the adopting individual."[14] In other words, an implementation may fail not because of the ineffectiveness of the innovation, but rather the ineffectiveness of the implementation process, which in the rehabilitation engineering case may include a lack of user training, caregiver support, or education. Such failure is often manifested as device abandonment subsequent to successful product development and adoption. By the time rehabilitation engineering R&D has generated a functioning device, significant investments have been made at multiple stages of knowledge transformation[3]: discovery, invention, and innovation, collectively entailing financial contributions from government funding agencies, universities, hospitals, and private sector partners (manufacturers, distributors, retailers, and investors). Unfortunately, estimates of rehabilitation technology abandonment are alarmingly high.[15-17] Thus, the system-wide cost of unsuccessful translation of rehabilitation engineering R&D is particularly steep.

With the ubiquity of information on health websites, condition-oriented online health communities, national and international rehabilitation technology repositories, and disability-related blogs, consumer participation in rehabilitation care is dramatically increasing, as in many other areas of health care.[18] Compounded with the affordability and omnipresence of power-packed consumer electronics, rehabilitation engineering is rapidly moving toward a distributed, nonelitist model of knowledge generation. Specifically, families and clients have been empowered through information technology and consumer electronics to become active cocreators of knowledge. The strategic management of this knowledge creation and translation partnership is an emerging challenge in rehabilitation engineering R&D. Further, with the knowledge democracy mediated by the Internet, we are witnessing the emergence of rehabilitation technologies with little, if any, clinical evidence. Consumers are thus laden with the burden of discerning between evidence-supported technologies and those for which clinical validation is still pending.

In light of the above challenges, we propose a knowledge ecosystem framework to describe KT activities in rehabilitation engineering R&D. Such a framework may help to identify mechanisms to further facilitate effective and timely KT.

List of abbreviations:

FES functional electrical stimulation
KT knowledge translation
R&D research and development
VMI Virtual Music Instrument

Rehabilitation engineering knowledge ecosystem

An ecosystem is generally understood to be a community of organisms living together interdependently within a physical environment[19] intricately bound by processes, such as the flow of energy[20] and cycling of nutrients.[21] As such, the ecosystem metaphor is particularly appealing as a framework for conceptualizing KT in rehabilitation engineering R&D. Figure 1 depicts an instantiation of a rehabilitation engineering knowledge ecosystem. The key process is the flow of knowledge, as indicated by the various arrows. The ecosystem is open in the sense that new knowledge can always be introduced into the system. Further, the ecosystem has inertia and knowledge evolving over time among its 3 states (discovery, invention, and innovation), borrowing from Lane and Flagg.[3]

It is important to mention upfront that figure 1 represents a simplification of reality in many ways. In actual rehabilitation technology R&D, there may not be clearly distinct demarcations among knowledge states nor would inputs and outputs necessarily be exclusive to 1 specific state. Further, knowledge flows may deviate from the pathways indicated. Nonetheless, we believe that the proposed framework is a useful tool for contextualizing and describing the complexities of the movement and transformation of knowledge in rehabilitation engineering R&D, cognizant of the reality that every project is a unique KT journey. In the following subsections, we elaborate on the various aspects of this ecosystem.

Knowledge inputs and outputs

The initial inputs into the ecosystem are the identified needs of clients and families (top box in fig 1), which we posit is a unique form of knowledge. The identified need might be described formally (eg, via a set of scores from standardized assessments) or informally (eg, as subjective observations of caregivers, teachers, employers, and family members). In any case, the need inherently embodies knowledge about functional and social goals, physical and cognitive capacities, preferences, health condition, occupational activities, physical and cultural environment, caregiver support and social network, among other personal and environmental contextual factors, relevant to a client or client group. Indeed, the works of Scherer,[22] Mirza,[23] Schaffalitzky,[24] and colleagues, among others, have signaled a shift in assistive technology prescription and delivery from an emphasis on the collective with disability to the unique values, preferences, and needs of the individual assistive technology user.

As in Lane and Flagg,[3] we identify 3 different codified knowledge outputs (shown on the right side of fig 1), corresponding to the 3 states of the knowledge ecosystem. In the discovery state, knowledge is generated via the scientific method, addressing a gap in literature, and yielding as output, scientific publications. In the invention state, knowledge is generated via development activities with a focus on demonstrating feasibility of a prototype in functional/therapeutic applications. The knowledge output of the invention state of the ecosystem can be described most broadly as intellectual capital, because this is knowledge with potential to produce commercial value. Intellectual capital encompasses not only legally enforceable intellectual property (eg, patents)[25] but also human capital (eg, knowledge, skills, and capabilities of rehabilitation engineers and clinicians), organizational capital (eg, institutional knowledge and experiences around therapeutic protocols or device testing methods), and social capital (eg, knowledge about client preferences and compliance, which is inscribed in relations among clinicians, researchers, and families).[26] Finally, in the innovation state, production methods facilitate the creation of knowledge about the economic utility of a rehabilitation technology, including its specific target market (eg, individuals with mobility limitations secondary to stroke), manufacturing (eg, applicable standards and requisite regulatory approvals), sales (eg, payees, price points), distribution (eg, local and global channels), and support (eg, service models). Complementing the formally documented knowledge, the ecosystem also generates as output, networked knowledge (discussed in a forthcoming section).

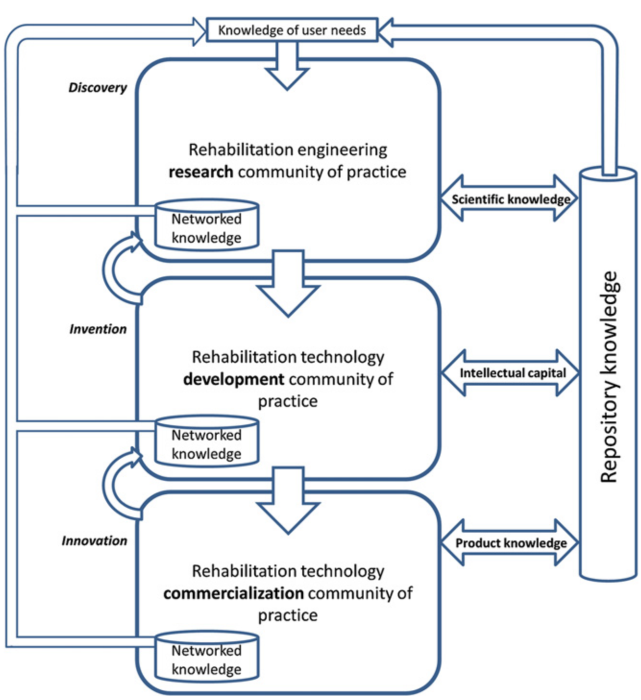

Fig 1 Rehabilitation engineering knowledge ecosystem.

Repository knowledge

In figure 1, the knowledge outputs (scientific knowledge, intellectual capital, and product knowledge) are collected in knowledge repositories. These repositories are not static, but are continuously updated with new outputs of the knowledge ecosystem. Drawing on connotations from computer science[27] and knowledge management,[28] we define the knowledge repository to be the collective store of formally codified knowledge from all 3 states of the ecosystem. From the discovery state, the repository thus encapsulates databases of scientific literature (eg, PubMed, conference proceedings). In the invention state of the ecosystem, formal knowledge sources would include international patent archives and engineering change order documentation packets[29] prepared in compliance with Food and Drug Administration and International Organization for Standardization requirements. In the innovation stage, rehabilitation technology databases (eg, European Assistive Technology Information Network), service history of rehabilitation technologies, consumer feedback, external product reviews, standard operating procedures (eg, as per International Organization for Standardization 9001 quality management systems requirements), and frequently asked questions may be among externalized, documented knowledge. The formal codification of knowledge in various repositories facilitates the reuse of existing methods in the design of new technologies, the synthesis of best practices,[29] and the identification of outstanding user needs. This latter function of repository knowledge is explicitly indicated in figure 1 by the arrow feeding back to the ecosystem input.

Clearly, these repositories are not only capacious deposits of rehabilitation technology-related information but become vast sources of shared knowledge.[28,30] As suggested by the 3 bidirectional arrows connecting the ecosystem states to the repository, knowledge can thus be retrieved from relevant repositories as needed to inform ongoing research, development, and production.

Networked knowledge and communities of practice

In addition to the formally documented knowledge, the rehabilitation engineering ecosystem is thriving with dynamic networked knowledge, that is, knowledge residing in human beings and created through ongoing interactions among individuals.[18] Kodama[31] contends that continuous business innovation is best served by networks of strategic communities that include universities, hospitals, private businesses, customers, nonprofits, among other potential players, all of whom share a uniform vision/mission,[32] a common concern, or passion about a particular topic.[33] These fluid and evolving communities are assembled on the basis of collaborative, interorganizational and often informal relations. The underlying premise of these communities is that innovation often occurs serendipitously between rather than exclusively within organizations. In applied health research, such communities of practice have also been recognized as fertile grounds for the cultivation of new ideas and sharing of knowledge.[33]

In figure 1, each state of the ecosystem invokes a community of practice,[34] albeit with potentially different memberships. For example, a community of practice for the invention state may include scientists, engineers, clients and families, clinical professionals, patent examiners, lawyers, commercialization managers, nonprofits, and funding agencies. Clinicians and families may share ideas with scientists about rehabilitation technology requirements and context of use, while lawyers may draw on their past experience with the U.S. Patent Office to advise scientists and commercialization officers on an intellectual property strategy for a particular rehabilitation technology. Allied health professionals may collaborate with engineers to propose the instantiation of a novel, scientifically informed rehabilitation technology. Indeed, a defining characteristic of community-based knowledge creation and sharing is the transcendence of disciplinary boundaries and perspectives.[32] The other key feature of the community of practice is its inherent sociability: knowledge is created and exchanged through the interactions of its members.[33,35] Unlike formal, codified knowledge, networked knowledge may grow and evolve rapidly.[31] Networked knowledge is akin to practice wisdom, acquired situated learning that derives primarily from practical experience, usually remaining tacit and undocumented.[10]

Knowledge producers and consumers

A community of practice within the rehabilitation engineering ecosystem does not privilege the knowledge of one member over that of another, fostering a culture of nonelitist, distributed knowledge. We thus examine more closely contributions of some of the key players in the ecosystem. Many members of the community function as both a provider and a consumer of knowledge.

Families and clients

In rehabilitation engineering, solicitation and consideration of client experiences, preferences, perceptions, opinions, and goals has long been routine practice in shared decision-making around candidate assistive technologies.[36,37] Additionally, families and clients bring to bear intimate knowledge about caregiver burden,[38] client and caregiver attitudes,[39] a client's daily routines and activities and opportunities for assistive technology support,[39] and treatment gaps and research priorities.[40] With the emerging shift toward consumer-driven health care service innovation,[18] many local rehabilitation services and researchers are witnessing unprecedented levels of consumer awareness around candidate rehabilitation technologies, both in terms of hardware (eg, tablet computers) and software (eg, apps).

There are wide-reaching benefits to assimilating family and client knowledge into discovery, invention, and innovation states of the ecosystem. To mitigate the risk of implementation failure, it is imperative that rehabilitation engineers embrace the family and client perspective from project initiation to completion.[41] The cultivation of family and client knowledge resonates philosophically with family-centered care, which encourages open dialogue between families and clinical professionals and caregiver empowerment.[42,43] Conversely, targeted knowledge transmission to families and caregivers can enhance a client's quality of care.[44]

Clinical professionals

In addition to knowledge stemming from their disciplinary training, health (eg, physiatrists, neurologists, developmental pediatricians) and allied health professionals (eg, occupational therapists, speech language pathologists, social workers, physiotherapists, recreational therapists, music therapists, nurses, psychologists, rehabilitation engineers) bring to the ecosystem their profound practice wisdom. This combination of disciplinary expertise and collective clinical acumen furnishes the ecosystem with valuable knowledge in numerous different R&D projects, including, for example, assistive technology testing and selection,[45] the design, implementation, and clinical trial of novel access technologies,[46,47] and the development and evaluation of technology-mediated treatments, such as FES therapy[48] or virtual reality therapy.[49]

As knowledge consumers, clinical professionals are key to the implementation and adoption of evidence-based technology-mediated interventions or evidence-supported rehabilitation technologies. Clinical professionals are in the best position to integrate research evidence, clinical expertise, and client values[10] within the context of iterative rehabilitation technology development and testing.

Public media

Media is identified by the Canadian Institutes of Health Research[50] as a potential channel for disseminating research to the general public. Indeed, print, radio, television, and the Internet are potent pathways for educating the public en masse about novel rehabilitation technologies[51] and technology-mediated treatments.[52] In this sense, media acts as a knowledge broker, facilitating the transfer of knowledge from researchers to families and clients. We remark that this is nonetheless a limited brokerage in that media does not provide formalized synthesis of research evidence, linking of decision-makers with researchers, or explicit promotion of the uptake of research evidence, which are key activities of knowledge broker strategies in health care.[53]

In addition to being a knowledge transmission mechanism, we argue (based on our extensive experience with media coverage of research) that media communications also play a knowledge production role in the rehabilitation engineering knowledge ecosystem. Specifically, journalists contribute valuable insight into the public mindset of the day, their appetite for and comprehension of information, techniques of capturing public attention, and an understanding of the audience at an emotional level, tactics not unlike those deployed in marketing.[54] We contend that this know-how is in fact knowledge that researchers do not possess. For example, to facilitate public consumption of research, journalists find strategic entry points, often at an emotional level, contextualizing new rehabilitation technologies in terms of care and quality of life challenges to which the public may relate. Oftentimes, to communicate unfamiliar scientific concepts to the general populace, journalists draw analogies to everyday phenomena. For example, to explain that mechanomyography is a low-frequency signal, journalists have likened the recording to the rumbling of thunder.[55] As a consequence of these lay perspectives, exchanges between media and researchers may lead to applications of rehabilitation technology beyond their originally intended domain.

Industry

In the knowledge ecosystem, industry includes any commercial entity (eg, manufacturer, distributor, start-up) that mobilizes the translation of invention prototypes into market-ready products. As such, industry partners as knowledge producers work with researchers and clinical teams to cocreate technology-specific production-relevant knowledge around the choice of materials, operating instructions, cleaning procedures, requisite user training, and choice of computing platform. Aside from decision-making around manufacturing strategy, industry plays a pivotal role in developing knowledge about potential markets (eg, customer demand, segmentation, and trends), competing products, reimbursement strategies, and distribution channels. As knowledge consumers, industry players in the rehabilitation technology sector clearly have potential to apply, produce, and market innovative products arising from rehabilitation engineering researchers, when those products align with a company's business strategy.

Although we typically only identify industry players (licensee or start-up companies, manufacturers, sales and marketing firms) in the innovation state of the knowledge ecosystem, there is emerging thinking around constellations of communities,[56,57] that is, the interconnection of communities of practice to augment knowledge creation, sharing, and translation. In this sense, one can imagine a macrocommunity of practice encompassing all knowledge producers and consumers across the ecosystem. In this constellation of practice, the industry participates fully throughout the knowledge ecosystem, from discovery through to innovation. The advantage of early industry engagement as a macro-community player in conjunction with lead users (users at the leading edge of a technologic trend) includes the potential to accelerate prototype development, facilitate transfer of knowledge, and increase commercial activities.[57]

Trainees

While academic faculty, hospital or industry-based scientists, and engineers in government or industrial laboratories are obvious knowledge producers, trainees at all levels and from a diversity of disciplines (eg, biomedical, electrical, computer, mechanical, or material engineering, biomechanics, kinesiology, occupational therapy, speech language pathology, physical therapy, social work, psychology, neurology, health policy, epidemiology, education, exercise physiology, life planning, nursing) also contribute to the rehabilitation engineering R&D knowledge ecosystem. Indeed, KT research has piqued the interest of many graduate students, residents, and fellows. In Canada, for example, this interest is evidenced by the trainee-led formation of the national Knowledge Translation Trainee Collaborative.[58] Specifically, in the rehabilitation engineering knowledge ecosystem, trainees as knowledge consumers interact with mentors, clinicians, clients, and families to acquire knowledge in areas such as *International Classification of Functioning, Disability and Health*-compliant terminology, system and experiment design, data analysis, technology evaluation, article and proposal writing, developing rapport with clients, communication to interdisciplinary audiences, among other scientific and professional skills. The trainee−mentor interaction is a classic example of knowledge externalization,[18] a concept introduced in the following section. As knowledge producers, graduate students, under the guidance of their mentors, are recognized as key contributors to journal publications in many fields.[59,60]

Knowledge flows

With a synopsis of some of the key knowledge stakeholders in the ecosystem, we now turn our attention to the knowledge flows that bind these players and others in communities of practice. Knowledge flow is defined as the transfer of knowledge from one person or place to another.[61] The knowledge encapsulated in the identified user need (top of fig 1) is iteratively transferred among producers and consumers, morphing from one state to the next,[3] eventually yielding a number of different codified (ie, repository) and tacit (ie, networked) knowledge outputs. Indeed, in product development, there is an inherent temporal flow of knowledge from preproduction through to postrelease.[30] Ultimately, the knowledge outputs cycle back (eg, consumer product feedback) to generate additional client needs as further inputs to the knowledge ecosystem. Additionally, as alluded to in Lane and Flagg,[3] knowledge may flow in reverse between states (indicated by the curved arrows), because downstream production knowledge may stimulate the enhancement of features of the invention or may reveal new client needs and hence trigger new research. Collectively, these various flows of knowledge are analogous to the cycling of nutrients through a biologic ecosystem.

At the community of practice level, there is a continuous exchange of knowledge among individuals. Within a community of practice, both tacit and explicit knowledge flows are valued.[35] Tacit knowledge is personalized and difficult to formalize or communicate, while explicit knowledge is codifiable knowledge.[62] These forms of knowledge correspond to our definitions previously listed for networked and repository knowledge. Nonaka's dynamic theory of knowledge creation[62] conceptualizes 4 possible knowledge flows involving tacit and explicit knowledge, each requiring different activities and each leading to the generation of new knowledge. Each flow is subsequently exemplified in the context of rehabilitation engineering knowledge creation and translation.

Tacit-tacit

An occupational therapist, speech language pathologist, and rehabilitation engineering scientist jointly assess a nonverbal client, observing expressive communication cues, motor function, motivation, posture, and interaction with mechanical switches. This knowledge flow/creation process is known as socialization, because knowledge is created through the interaction of 2 or more people in some shared experience, conducive to the mutual extraction of tacit knowledge.

Explicit-explicit

A patent lawyer and a rehabilitation engineering scientist meet to review prior art and research publications arising from the scientist's lab, ultimately drafting a set of claims for a new patent. This process is called combination, where codified knowledge held by different individuals is combined to form new knowledge.

Tacit-explicit

Scientists conduct a study whereby frontline nursing staff is interviewed to document the ethical discernment practices of proficient nurses.[63] This knowledge flow is known as externalization, because the interactions among individuals aim to expose and concretize tacit knowledge and therefore others may in turn acquire such knowledge. In rehabilitation engineering development projects, externalization of project-relevant knowledge of individual team members prevents knowledge loss.[29]

Explicit-tacit

Physiotherapists are presented with a meta-analysis of clinical evidence around effective regimens for restoring sitting function in spinal-cord injured patients and subsequently contemplate how this evidence will impact their clinical practice with their respective clientele. This process is aptly labeled internalization, where individuals integrate explicit knowledge with their own experiences, internalizing new tacit knowledge. Internalization resembles the integrative approach to conceptualizing evidence-based practice.[10]

Fundamentally, the flow and creation of knowledge necessitates social interactions among the various producers and users.[18] Certainly, in rehabilitation engineering R&D, the multifaceted nature of identified client needs typically demands multidisciplinary team involvement, methodologic pluralism, and thus multiple, distributed knowledge flows. The notion that these multiple, bidirectional, and socially enabled flows yield new knowledge closely parallels the Canadian Institutes of Health Research's definition of knowledge exchange as "an interaction between the knowledge user and the researcher, resulting in mutual learning."[50]

Case examples

We illustrate the application of the knowledge ecosystem as a tool for framing the KT activities relating to 2 rehabilitation engineering R&D endeavors, one being an assistive technology device and the other being a technology-mediated therapy.

Bloorview Virtual Music Instrument

In 2002, families, teachers, and clinicians at Holland Bloorview Kids Rehabilitation Hospital (Canada), a teaching hospital of the University of Toronto, identified a pining need to more fully engage children with severe motor disabilities. The concern was that because of limited voluntary movement, many of these children were missing opportunities for physical and cognitive development. Instead, they were becoming increasingly passive, lacked motivation, and were at a heightened risk for developing learned helplessness. This unmet need was echoed in literature.[64] Commercially available access solutions involving mechanical switches had failed for these children because of issues of inconsistent switch targeting, slow switch release subsequent to activation, elusive switch positioning, and multiple switch activations, among others (see Chau et al[65] for more details).

Figure 2 is an instantiation of the proposed ecosystem model for this particular case example, summarizing some of the key KT activities relating to the Virtual Music Instrument (VMI). A team of concerned individuals was created at the urging of a rehabilitation engineer. This discovery community included several occupational therapists, a psychologist, a developmental pediatrician, a music therapist, an educator, a music scientist, and the said rehabilitation engineer. With several external grants, a subset of this community began to explore noncontact alternatives, given the numerous challenges associated with contact-based switches. A camera-based solution soon surfaced as a promising noncontact pathway given the wide range of movements that could be flexibly accommodated. Through several research projects, this community investigated children's contingent awareness of sound generation through a simple noncontact computer vision-based technology.[66] The team found that despite the lack of tactile feedback, children as young as preschool age easily grasped the concept of cause-and-effect in the context of a custom-designed, virtual computer environment where sounds were triggered by gross physical motion (eg, waving of one's arms). Key knowledge flows in this discovery phase included tacit-tacit flows between occupational therapists and rehabilitation engineers, identifying the types of movements made by children that ought to elicit auditory feedback and the nature of the feedback (eg, single tones vs entire musical motifs), which reinforces cause-and-effect.

These early studies led to the development of the Bloorview VMI, a webcam-based motion detection system that translates movements into music. Figure 3 shows a young boy using the VMI in music therapy. Here, he is activating virtual objects with his head and hands in the context of a collaborative music-making activity with a music therapist (who was playing the piano). See Chau et al[65] for a detailed explanation of the technology's operation. Through iterations between discovery and invention states, the device evolved from a simple motion detection system to a bilateral upper extremity tracking system to a spatially targeted motion detection system. Correspondingly, the music feedback started as prerecorded Music Instrument Digital Interface songs to rhythm and melodic riffs generated on-the-fly, to, finally, a single tone output.

Outputs from evaluations of the invention included several publications[65,66] demonstrating clinical benefit, including new opportunities to participate in play, improvement in psychosocial skills and body function, enhanced maternal satisfaction, and positive impact on family dynamics.[67] Given the involvement of a music therapist from project inception, this knowledge was quickly translated into a new clinical program (music therapy using the VMI) at Holland Bloorview. Today, this program serves outpatients with various conditions (eg, cerebral palsy, autism) and inpatients in complex continuing care (eg, degenerative neuromuscular conditions), targeting various developmental goals, including, but not limited to, increasing social interaction, improving active participation and engagement, enhancing motor skills, and augmenting expressive communication. This evidence reached a children's rehabilitation center in South Australia via a rehabilitation engineer who interned at Holland Bloorview. As a consequence, the VMI has also been integrated into curricula activity at specialized schools for children and youth with disabilities in both Canada and Australia.[65] These clinical adoptions[10] of the VMI can be likened to early adoption of technology

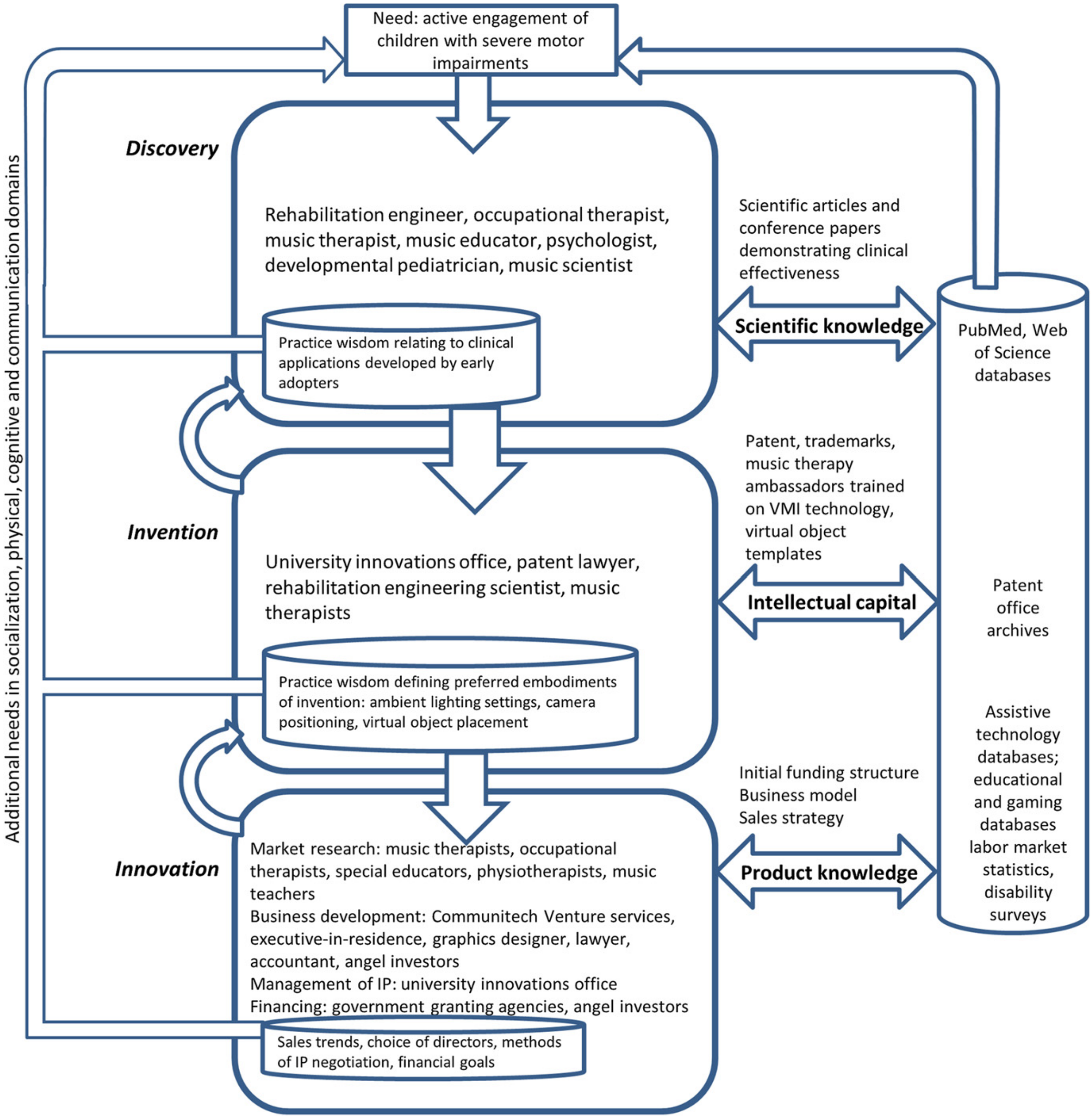

Fig 2 Knowledge ecosystem for the VMI rehabilitation technology: from need to product. Abbreviation: IP, intellectual property.

by the peer community of lead users,[57] prior to any substantial commercialization effort.

Through collective efforts of the university innovations office, a patent lawyer, and the rehabilitation engineering scientist, intellectual capital arising from the invention state included a patent filing, international trademarks, and the training of a dozen local music therapists on the clinical deployment of the VMI. Significant networked knowledge was generated in the form of practice wisdom through interactions among therapists, engineers, and clients. Specifically, knowledge was generated around optimal camera positioning relative to the client, ambient lighting settings, optimal sensitivity and movement filter settings for clients with different movement quality (eg, hyperkinetic vs spastic movements), and strategic placement of virtual objects. On the latter point, tacit knowledge of therapists was externalized in the form of templates of virtual objects (stored as digitized files readable by the VMI software) that families and other clinicians could port to their own environments to replicate specific musical activities.

The innovation stage of the VMI KT journey was arguably the most complicated in terms of stakeholders and knowledge flows, as suggested by figure 2. Multiple external sources of knowledge were brought to bear to support market research, business development, intellectual property management, and financing of the VMI commercialization efforts. Information was exchanged among

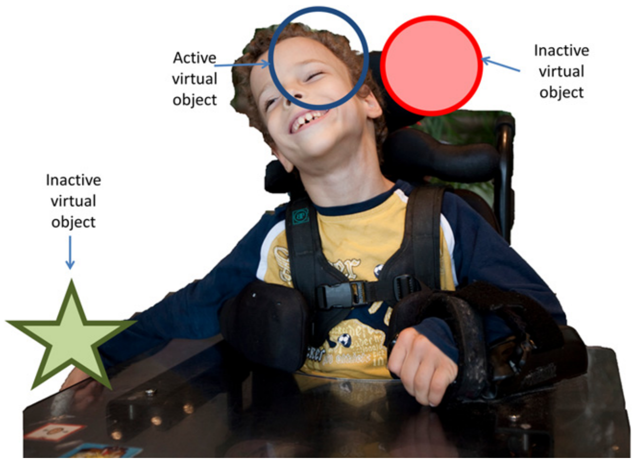

Fig 3 Pediatric client using the VMI in music therapy. Photo reprinted with permission.

these multiple partners primarily through the coordination of a cofounder of a spin-off company. The outputs of this stage included both codified knowledge (eg, business plan) and tacit knowledge (eg, approach to intellectual property negotiations). Product testing and usage in invention and innovation stages resulted in important consumer feedback relating to necessary product enhancements and the identification of software bugs. Furthermore, the years of beta-testing also revealed additional client needs in socialization (eg, increase attention span and social acknowledgment as in eye contact), physical (eg, maintenance of motor function), cognitive (eg, increase vocabulary comprehension), and communication (eg, improve pitch perception) domains, all of which pose additional opportunities for clinical research and further discovery (feedback arrows from the ecosystem states back to knowledge input in fig 2).

Stimulator project

The instantiation of the knowledge ecosystem model for the second case example, the stimulator project, is presented in figure 4. According to the American Heart Association,[68] more than 700,000 people annually in North America have a stroke, and more than 4 million live with the consequences of stroke. Stroke is the leading cause of disability, costing the American health care system approximately $43 billion per year. Stroke often causes partial or complete loss of limb function (both arms and legs are affected). FES is a means of generating muscle contractions through the delivery of a series of transient electrical pulses.[69] FES has been used for assisting individuals with spinal cord injury or stroke in performing tasks such as grasping objects and walking.[70] However, the major shortcoming of commercial FES technologies to date has been the lack of concordance between the biologic pattern of efferent stimulation of muscles and the pattern of externally generated stimulation signals. This discrepancy precludes cortical recognition and relearning of the task via proprioceptive feedback. As a consequence, commercial products, such as the H200 hand stimulator and drop foot stimulators,[a] have had limited success in retraining the brain to perform targeted muscle contractions.[71] In the discovery phase of this project, randomized controlled trials with physiologically inspired stimulation patterns indicated that intensive motor training with FES can indeed restore voluntary control of limbs in individuals with hemiplegia and spinal cord injury to the point where external stimulation itself is no longer needed.[70,72] Following these findings and given the large number of individuals who could potentially benefit from FES therapy, scientists at the Toronto Rehabilitation Institute (Canada), a teaching hospital of the University of Toronto, were motivated to develop and commercialize a stimulator that mimicked efferent muscle stimulation in order to restore voluntary control in individuals with spinal cord injury or poststroke.

In the invention phase, the community of practice consisted of development and clinical trial teams. The development team consisted of engineers (electrical, software, and neural), physiotherapists, and occupational therapists. The development of FES therapy in Toronto started with the creation of a prototype FES stimulator. This development required 4 to 5 years to complete and was conducted in collaboration with various industrial partners, most notably a company in the business of electrical stimulators. Figure 5 depicts an individual performing a block manipulation task with the help of FES. Subsequent to prototype development, a clinical trials team (physicians, allied health professionals, and a neural engineer) started to conduct pilot trials, followed by phase I, phase II, and later phase III randomized controlled trials to test the clinical effectiveness of the technology. Some of these trials are ongoing at the time of writing. Because 2 phase II randomized controlled trials[70,72] demonstrated the efficacy of FES therapy in 2 different patient populations, the team (led by the neural engineering scientist) decided to pursue the commercialization of the technology. The team was unable to find industrial partners to help commercialize this technology, because none of the companies in the stimulation arena at the time had biomimetic stimulation products. As a consequence, the team created a start-up company.

In this example, the boundaries between the invention and innovation states of the ecosystem were blurred, and knowledge in the form of intellectual property and business strategy developed simultaneously. Once the start-up company was established, the founders started to apply for government funds designated for taking new and innovative technologies to market. However, funding to translate knowledge from the discovery to invention and innovation states was difficult to secure by the founders (scientists and engineers), despite multiple attempts and the myriad of funding programs dedicated to translating ideas to products. Nonetheless, the team was successful at attracting funding to conduct further clinical trials and research. In retrospect, the community of practice for this phase of knowledge transformation was incomplete. The said funding programs required that applicants possess considerable business acumen, knowledge that scientists typically do not have. Full transition between invention and innovation thus lasted $\geq$3 years, until the team recruited an individual with considerable business and start-up expertise. This individual brought practice negotiation experience, familiarity with government funding programs, and deep connections within the investment and business development networks to the community. This individual eventually became the chief executive officer of the start-up company.

The next hurdle in the invention to innovation knowledge transformation was the negotiation of license agreements with institutions (university and teaching hospital) where the technologies were originally developed. After completion of the license agreements, filing of patent applications ensued, as well as the creation of the manufacturing capabilities to produce a product that would meet regulatory requirements. In this case, while there were arguably knowledge flows among the various stakeholders,

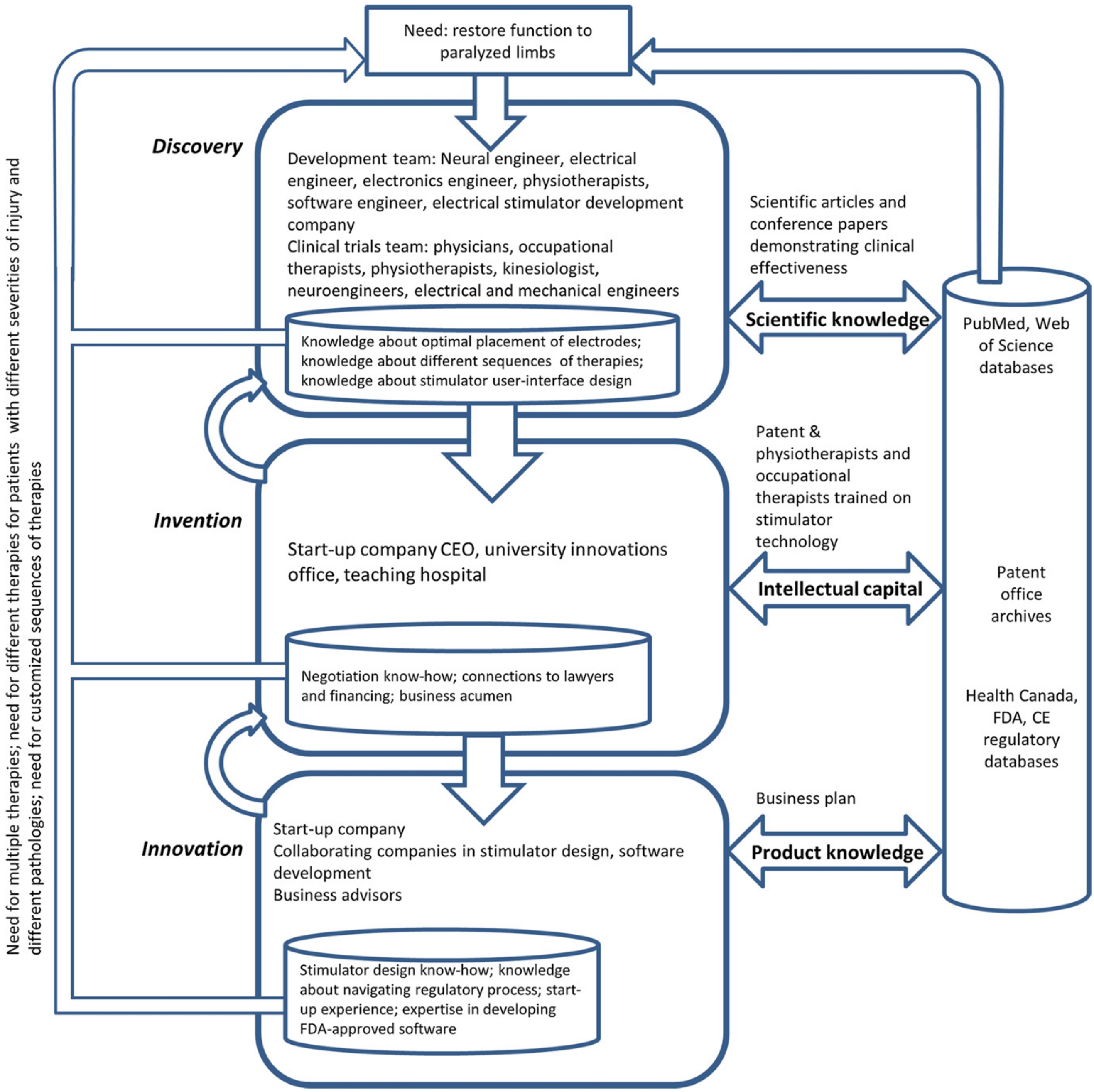

Fig 4 Knowledge ecosystem for the stimulator technology: from need to product. Abbreviations: CE, Conformité Européenne; CEO, chief executive officer; FDA, Food and Drug Administration.

the principal facilitator of knowledge externalization (tacit-explicit) and combination (explicit-explicit) was the chief executive officer of the start-up company.

Throughout the various knowledge transformations, new knowledge about patient needs emerged (arrows feeding back to the patient need box in fig 4). For example, through clinical testing, it became evident that patients with different pathologies and different injury severities required customized sequences of FES therapies. This knowledge in turn catalyzed additional clinical research.

In both the stimulator and VMI examples, what is particularly remarkable is the amount of time required for knowledge to flow through the ecosystem, from discovery through innovation. In the VMI example, the path from discovery to innovation required more than a decade. The technology, however, had been deployed clinically in service programs at the local rehabilitation hospital since early on in the discovery process. Similarly, in the stimulator example, the technology to deliver the therapy was 10 years old by the time the innovation state of the knowledge ecosystem was reached. Clinical utility had been confirmed 4 years earlier. The associated therapy could not be made available, even to patients treated in the institution where the stimulator technology was originally developed. A key reason is that the stimulator technology is classified as a Food and Drug Administration class II medical device, and thus cannot be clinically deployed prior to appropriate regulatory approvals.

Fig 5 Object manipulation training using FES therapy in individuals with spinal cord injury. Photo reprinted with permission.

Conclusions

We have introduced a knowledge ecosystem framework for describing the intricate knowledge flows in rehabilitation engineering R&D among multiple knowledge producers and consumers, beginning from the knowledge of an identified clinical need through to the knowledge around the application of a new, commercially available rehabilitation technology. Our framework is built around the notion of a trichotomy of communities of practice, and the dynamic interactions of its members in the generation and exchange of networked and repository knowledge. Two real-life embodiments of this framework demonstrate its potential utility. The documentation of successful rehabilitation technology KT experiences in terms of the proposed knowledge ecosystem may help to inform future research-development-commercialization initiatives in the field, in terms of the requisite knowledge stakeholders within various communities of practice, the dynamics of knowledge flows, and the necessary repository and networked knowledge at each ecosystem state.

Supplier

a. Bioness Inc, 25103 Rye Canyon Loop, Valencia, CA 91355-5004.

Keywords

Activities of daily living; Knowledge; Occupational therapy; Rehabilitation; Self-help devices; Technology transfer

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