# CREATING COMPETENCIES FOR RADICAL TECHNOLOGIES: REVISITING "INCUMBENT-ENTRANT" DYNAMICS IN THE BIONIC PROSTHETIC INDUSTRY

**Abstract:** Defining radical technologies based on their effect on existing technological regimes, scholars have studied incumbent-entrant dynamics based on whether incumbents can offset the obsolescence of their technological capabilities by utilizing complementary capabilities or by adapting to technological change. We identify important limitations stemming from such a definition of radical technologies and utilize the alternative definition of radical technology as a technological system that utilizes new base principles at either component or system level. Our study examines how radical technological systems are created by economic actors that are heterogeneous in both their prior history and their experimentation efforts, and the implications for their value capture strategies. We utilize historical methodology to analyze rich quantitative and qualitative data on the incubation and commercialization of bionic prosthetics. We show that the component knowledge for the new technological system was created by diverse firms—startups, conventional prosthetic incumbents, and established firms in other industries. However, incumbents who invested in the new technology system were key to creating an integrated system for bionic prosthetics and dominated in commercialization efforts in the nascent industry. Startups captured value through licensing or being acquired by incumbents, and established firms in other industries were knowledge spillover conduits, given their focus on alternative nascent downstream markets to capitalize on their existing capabilities.

**Keywords:** Technological change, nascent industries, technological system, competitive dynamics

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# INTRODUCTION

Radical technologies are often at the base of new industries (Gort & Klepper, 1982; Rosenberg, 1963; Tushman & Anderson, 1986). Using an economic effects approach, scholars have often defined radical technologies as exogenous technological shocks that render existing technological competencies of established firms obsolete (Arrow, 1962; Henderson, 1993; Tushman & Anderson, 1986). A rich literature on incumbent adaptation to technological change ushered by entrants has examined how other capabilities may buffer incumbents from the effects of radical technologies—these include specialized complementary assets (Teece, 1986; Mitchell, 1989; Tripsas, 1997), dynamic capabilities (Chen, Williams, & Agarwal, 2012; Helfat & Raubitschek, 2000), and sense-making and adaptation capabilities (Eggers & Kaplan, 2009; c.f. Eggers & Park, 2018).

In this paper, we revisit the potentially tautological definition of radical technologies and obsolescence of incumbent technological capabilities. We frame the concept of radical technologies in terms of the technological system being utilized to provide solutions to human needs by leveraging insights from the theory of technology (Arthur, 2009; Baldwin, 2016; Goldfarb & Kirsch, 2020; Rosenberg, 1963). In doing so, we separate the nature of technological change (i.e., what is a radical technology) from where the capabilities necessary for the radical technology reside. We thus build a framework to examine the strategic and performance consequences of radical technologies. Specifically, we examine how heterogeneous firms—incumbents, diversifying entrants, and startups—may be differentially positioned to create requisite knowledge for the new technological system and how this shapes their subsequent value capture strategies.

We illustrate our approach in the context of bionic technology that has profoundly transformed the prosthetic limb industry. Prosthetic limbs are medical devices in orthopedics and physical medicine that are fitted to amputees in order to restore lost functions of natural limbs. Prior to 1997 and even to date, the dominant technological solutions utilized mechanical science and engineering for the creation of artificial limbs and their fit and functionality (interface) with residual limbs. Bionic prosthetics—also referred to as “robotic limbs,” “robotic assistive technology,” or “active prosthetics” infuse electronic engineering, robotics, and neuroscience/artificial intelligence principles to incorporate electrically powered control systems, interfaces that provide sensory feedback, and self-learning and adaptation of the prosthetics for greater functionality and ease of use. Bionics were radical in that they leveraged new natural effects, such as electronics, to control prosthetics.

Following Goldfarb & Kirsch (2020), we think of technological solutions as systems that are both anchored in physical technology and transcend into the socio-economic system that delivers value. When some or all of the physical technological core is replaced with a new, radical solution, existing technologies, together with subsequent improvements to the new one, are integrated into a new technological system. In the bionics prosthetics industry, the technological capabilities necessary to develop and provide useful customer solutions were distributed across incumbents, diversifying entrants and startups— and all three firm types played important roles in a new industry emerging from a radical technology. Incumbent prosthetic firms who made technological investments in the nascent market were the most likely to introduce products into the market, and these firms leveraged the convergence of old and new technologies. Technology-based startups cooperated with incumbents through licensing and acquisitions. This suggests that startups’ new bionic capabilities complemented capabilities of incumbent prosthetic firms. In the process of technological convergence, established firms from other industries took advantage of newfound complementarities between their existing capabilities and new ones applicable to the nascent bionic prosthetic industry to enter the market in spaces not directly competing with incumbents. Firm business histories reveal that conventional prosthetic firms invested more actively in existing technology than other types of firms. Knowledge related to developing and offering products in the conventional prosthetics market was critical to product development and commercialization in the bionics prosthetics markets. The effect of the radical technology that was bionic prosthetics was a function of the existing technological capabilities and their degree of complementarities with the new bionic approach. We then argue that careful consideration of if and how a specific radical technology fits within an existing value delivery system provides a more general framework to understand the effect of radical technologies on incumbents, entrants and diversifiers strategic choices.

We thus contribute to existing work on industry evolution and disruption in strategic technology management. Considering the structure of technological solutions and its interaction with organizational capabilities provides a framework to evaluate how radical technologies might affect strategic positions of firms in an industry.

## CONCEPTUAL BACKDROP AND RESEARCH QUESTIONS

### Brief Literature Review on Economic Effects Based Definition of Radical Technology

Radical technology has predominantly been defined based on its "economic" effect on technologies associated with incumbents within a focal industry (as composed of firms who provide products and services using the technology). Here, Tushman and Anderson (1986: 440) define technology based on its economic functionality: "[technology is…] those tools, devices, and knowledge that mediate between inputs and outputs (process technology) and/or that create new products or services (product technology)" In seminal work, Arrow (1962) defines radical (drastic) innovations as an advance that renders the old technology as no longer a viable substitute, and notes that incumbents, particularly those who are monopolists and/or possess market power, will lack the incentives to undertake optimal investments in radical innovation. Similarly, Tushman & Anderson (1986: 441) define radical technologies as major discontinuities that offer "sharp price-performance improvements over existing technologies." Moreover, they distinguish between radical technologies that are "competence-enhancing or competence destroying" based on their effect on incumbent capabilities, noting in particular that "both technological discontinuities and dominant designs are only known in retrospect—technological superiority is no guarantee of success" (Tushman & Anderson, 1986: 443).

Continuing in this vein, seminal scholars noted innovations that destroy incumbent competencies are more likely to be introduced by entrants, and are therefore radical (Gort & Klepper, 1982; Tushman & Anderson, 1986; Henderson, 1993). In early work, entrants were often assumed to be small and new startups in line with Schumpeter's theory of creative destruction (Agarwal & Audretsch, 2001; Henderson, 1993). Later work recognized that entrants include established firms in other industries who possess relevant technological capabilities (Bayus & Agarwal, 2007; Klepper & Simmons, 2000; Sosa, 2013), and even startups benefit from their founders' prior knowledge context (Agarwal & Shah, 2014). However, incumbents in the focal industry, in addition to a lack of incentives (Arrow, 1962; Reinganum, 1983), are theorized to exhibit inertia due to "historical experiences" manifested in existing structures or cognitive attention (Tushman & Anderson, 1986; Henderson, 1993).

A substantial body of literature has built on the above premises of seminal work. In their comprehensive review, Eggers and Park (2018) note that faced with radical technological change, incumbents are either doomed, or may possess differential abilities to adapt so they can survive and even thrive across technological discontinuities. Important for our context is that this entire literature stream is framed as a study of "antecedents allowing (or inhibiting) incumbent firms to adapt to (exogenous) technological change" (Eggers & Park, 2018: 360). Given (competence-destroying) radical innovation by definition renders incumbent technology obsolete, the antecedents of adaptation efforts necessarily focus on factors other than technological capabilities. Chief among these are complementary capabilities (Helfat & Lieberman 2002, Mitchell 1989, Tripsas 1997), (dynamic) capabilities that facilitate acquisition and assimilation of the new technological knowledge (Cattani, 2005; Eggers 2012; Franco, Sarkar, Echambadi & Agarwal, 2009; King & Tucci, 2002; Sosa, 2013 ), and cognitive attention, including the willingness to cannibalize existing product lines (Benner & Tushman, 2002; Chandy & Tellis, 1998; Eggers & Kaplan, 2009; Tripsas & Gavetti, 2000)

Eggers & Park (2018) also observe that the empirical context of most if not all of the above studies are single industries. Given the retrospective nature of the definition of radical innovation, many of these industries are sampled based on whether there was a successful and complete displacement of technologies. Moreover, the studies track inception of the industry as the first instance of commercialization of a product to study incumbent-entrant dynamics, examining entry based on introduction of products embodying the radical innovation, and technological capabilities of entrants based on key technological performance dimensions.

## Brief Literature Review on Radical Innovation defined based on nature of technology

We follow a long line of scholars who define technology without regard to its economic impact. Rosenberg (1973) simply uses the word technique, which is a "method of accomplishing some desired aim" [1], and explicitly points out that this need not be an improvement over existing solutions. Rosenberg later added in conversation with one of the authors that a technology is something you can "drop on your foot".[2] Arthur (2009), also adds materiality explicitly. Put something, a technology is the thing that *does* something for a human purpose.[3] We define

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[1] https://www.merriam-webster.com/dictionary/technique

[2] Personal conversation between Nathan Rosenberg and Brent Goldfarb, 1998.

[3] See Arthur (2009, Ch. 2) for an extensive and thoughtful discussion of this definition. How to put construct this means, and any understandings of why it works is knowledge. This definition is consistent with Mokyr's distinction between scientific knowledge and technology (CITE). Arthur is far from the first to consider materiality an important aspect of a technology (see Goldfarb & Kirsch, 2020 for a discussion), as arguably this is what distinguishes a technology from a technique. A question arises as to whether insisting on materiality would exclude software or algorithms as technologies. However, software and algorithms must be implemented on hardware to actually do something and be economically meaningful.

technological systems as architected assemblages of such methods. Whether that technology becomes a product or service is not a criterion for consideration as a technology. An alternative definition of radical innovation abstracts away from the economic or organizational effects and focuses instead on the nature of technology. Arthur (2007: 277) elaborates further on the nature of technology to note "A technology...possesses a purpose, a combination of components, an architecture, and embodies a base principle that exploits some base phenomenon." i.e. a technology is the use of base principles to assemble a working architecture from components--the components themselves may represent "sub-technologies" such that the working architecture may consist of hierarchies that span across several layers.[4] [5]

From this it follows that a definition of radical innovation should abstract away from the economic or organizational effects and focuses instead on the nature of technology. Arthur (2007: 278) offers that a radically novel technology as one that "achieves a purpose by using a new or different base principle than used before", and notes than "translating this base principle into physical reality requires the creation of suitable working parts and supporting technologies," some of which "may require inventions of their own." Thus, a radical innovation entails "matching a need to a principle (or effect envisaged in use) and solving the hierarchy of problems and subproblems that this creates."

Arthur further conceptualizes technology as an "exploitable effect" of the principle, while invention is the linking of these effects to achieve a solution for a human need. Importantly, "systems" or "assemblies" of technologies are needed in order to achieve solutions. In fact, the co-

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[4] As Arthur (2007: 277) elaborates: "Technology is a means to fulfill a purpose, and it does so by exploiting some effect. It consists of a central assembly--the overall backbone of the device or method that executes its base concepts (and exploits one or more base effects) plus other assemblies hung off this to make this workable and regulate its function. These components or assemblies function together in a working architecture. To understand a technology means to understand its principle and how this translates into components that share a working architecture"

[5] The closest to this definition in the organizations and technology management literature is the view by Henderson and Clark (1990) of technology as consisting of core design concepts embodied in components that are linked together in an architecture and define radical innovation as the use of new design concepts and architecture.

dependence of technologies makes the classification of individual technologies challenging, and the usefulness of one technology is highly dependent on the development and usefulness of others. (Rosenberg, 1979). The converged system of technologies, in turn, is often bundled in a way that is classified as a unit. More precisely, each technology is an assembly of diverse sub-technologies, where each sub-technology in turn is an exploited natural effect. For example, the technology of "radio" exploits the natural effect of electromagnetic waves for the purpose of transmitting information. Early radios systems used simple electronic subtechnological components such as resistors and capacitors that were recombined to make a working radio. However, early radios embodied other converging technologies, such as the use of vulcanized rubber to isolate wires, wood working to encase the sets, etc.

In this sense, technologies represent recursive solutions to prior problems that recombine different sub-technologies. That is, they are systems. Through the innovation process, some or any of these sub-technological solutions, or the way in which they are combined, may be radical if they rely on a new natural principle. That is, radical sub-technologies will be combined with multiple existing and established technologies for certain aspects of a solution. For example, some early automobile manufacturers combined existing (non-radical) horse-carriage technology with a radical solution for propulsion, the internal combustion engine. The novelty of radical technologies implies a fundamental level of uncertainty around the technical and economic feasibility of such re-combinations. Mokyr summarizes earlier insights from Rosenberg (1979, p. 31) eloquently where he notes that radical technologies may "raise the marginal product of effort in development, and thus lead to a sequence of further improvements" (Mokyr, 1990: 352). This happens as they resolve some bottlenecks, and highlight others (Rosenberg, 1963; 1979; Goldfarb & Kirsch, 2020). Over time, the architecture of horseless carriages was modified to achieve better vehicle performance (Pillai, Goldfarb, & Kirsch, 2020). This required the use of some new base principles that were radical in the vehicle setting, such as the use of rubber and tires. But it did not require a radical rethinking of the use of the wheel. That base principle remained unchanged. Thus, whereas the engine was radical, the technology that was the automobile relied on many known technologies that were incrementally improved, over time, to better complement the capabilities of the new propulsion technology (see the seminal exposition of this process in the context of machine tools by Rosenberg (1963)). More generally, radical technologies may unleash waves of new economic experimentation, wherein both failed and successful efforts generate valuable information regarding the trade-offs encountered in both the recombination of scientific principles and their economic implementation (Rosenberg, 1992). In part, a failure to take this systems approach into account obscures our understanding of how the radical technology impacts firms.

## Creating Competencies for Radical Innovation: Integrating the Nature of Technology with the Role of Economic Actors

When considering both definitions of radical innovation in tandem, each reveals an important gap in the other. The first gap is that a predominant focus on incumbent-entrant dynamics post industry inception conflates the economic effects and prior history of organizations in the definition of a radical innovation. The second gap is that the literature on the nature of the technology abstracts away from microprocesses undertaken by economic actors in terms of heterogeneous strategies for the creation of the radically new technological system and subsequent value capture. We elaborate on each gap below to motivate the two conceptual premises for our study.

The first conceptual premise is the need to separate the nature of radical innovation from its economic effects (as guided by the literature on the nature of technology). The second conceptual premise is the need to incorporate the role of economic actors and their strategic considerations in the creation of a radical technology, an issue that has not received as much attention in technology studies noted above.

### Need to Separate Nature of Radical Innovation from its Economic Effects

Using the definition of radical innovation based on the nature of technology helps address several issues with the literature reviewed in the first sub-section above that conflates causes and effects of radical technologies vis-à-vis organizations. First, it avoids a circular definition of radical innovation based on "market test"—by defining a radical innovation based on whether the base principles are different between the new and the old technology, it allows for a separation between attributes of an innovation and which organizations possess relevant technological capabilities. For example, biotechnology utilizes different base principles related to biology (living organisms), which are fundamentally different from earlier products and services serving the same purpose that utilized base principles related to chemistry (chemical synthesis). Such use of base principles does not *have to* map onto organizational capabilities of incumbents and/or entrants, even though they *may*.[6]

Second, conceptualizing a (radical) technology as the use of base principles to assemble a working architecture from components that may themselves represent (new) sub-technologies obviates defining radical technologies based on a one-to-one correspondence with obsolescence/substitution of incumbent technologies. The utilization of different base principles may occur at either a system or a component level, moreover, the number of components and linkages within an architecture may also be subject to change. When understood as a *technological system,* trees can grow wider and deeper (i.e., more complex) in terms of new components and

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[6] Of note is the recent news (Loftus, Hopkins & Panceviski, 2020) regarding COVID vaccines developed using mRNA technologies rather than conventional methods relying on vaccines that inject antigens (a piece of the virus) into the body. Both Pfizer (an established firm) and Moderna (a startup) announced variants of mRNA technologies in quick succession of each other. Meanwhile other organizations--established firms and startups alike—are using conventional technologies for COVID vaccines too. Thus, the useful distinction between mRNA based and conventional vaccines is not *who* introduced the technology, but *what* was the difference in base principles.

architectural knowledge. New component and architectural knowledge will be radical in this case, but the change will not always make all of the old capabilities obsolete. Relatedly, this definition removes the need to create broad classifications of radical technologies as competence destroying or competence enhancing based on whether they were introduced by incumbents vs. entrants. For example, Tushman & Anderson (1986) classify electric typewriters as a competence enhancing discontinuity relative to mechanical typewriters. In part, this may be because some features of the typewriter's architecture were retained (e.g., Qwerty keyboard), and in part it may be because, looking retrospectively, electric typewriters were dominated by incumbents (e.g., IBM; Remington Rand) by the nineteen forties.[7] A focus on base principles permits the classification of the technology as radical because of the shift from mechanical to electrical principles, and concomitant changes in components and architectural redesign. Moreover, it allows for the recognition that changes in base principles *need not* create obsolescence and substitution of *all* component knowledge even though they *may*—some retain value due to either underlying principles or because of endogenous choices by organizations to retain design elements.

Third, a separation of the features of radical technology—the use of different base principles to achieve a purpose—from its impact—substitution of existing technologies—allows for a re-examination of industries where radical and existing technologies may co-exist because they cater to different purposes which may manifest in different price-performance parameters. In such cases, radical technologies can create eras of ferment where incumbents and entrants alike engage in

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[7] Interestingly, archival reports (IBM archives, Rehr) indicate that electric typewriters were first introduced by Northeast Electric Company, based on licenses of patented technology created by an independent inventor John Smathers. Northeast Electric initially contracted with Remington for the production of the Remington Electric Typewriter in 1925, and when subsequent negotiations fell through, Northeast Electric entered the market with its own product in 1929. The firm's typewriter business was later spun off as Electromatic Typewriter Co. when Northeast Electric was acquired by General Motors. Electromatic Typewriter Co. was subsequently acquired by IBM, which introduced its first electric typewriter—the 1933 IBM Electromatic in 1933). Thus, this early history of electric typewriter technology would indicate that competencies did not emerge from incumbents themselves but were acquired by them through alliances or acquisitions.

capability investment and product entry, with neither the need nor fear of cannibalization concerns. For example, in the medical diagnostic industry, entrants and incumbents alike invested in technologies that relied on different base principles (e.g., X-ray, magnetic resonance, nuclear medicine). These technologies themselves cater to different needs (e.g., bones vs. tissue and organ scans) and offer different price/performance tradeoffs. Defining radical innovation based on changes in base principles to achieve a purpose allows for the potential that technologies and/or the organizations associated with them *need not* be in direct competition with each other, even though they *may*.

Fourth and related to the above three points, separation of the nature of the technology from its economic cause and effects relaxes the need for sampling on industries that adhere to the obsolescence definition and opens up the examination of industries born from technology convergence and/or general-purpose technologies that have applications across different industries (Rosenberg, 1979). For example, digitization as a general-purpose technology created a change of base chemical to digital principles in imaging industries, and additionally required a convergence of capabilities previously distributed among firms in imaging, consumer electronics and computer industries. Similarly, a change in base principles to enable communications within and across wired vs. wireless technologies required a convergence of capabilities previously distributed among firms in telecommunications, computer (Internet) and cable industries. Radical technologies that are either general purpose and/or represent convergence require creation of altogether new technological systems aimed towards specific purposes, even if the component technologies may themselves not be radical themselves. This also means that the capabilities required for, and/or rendered obsolete by, radical technologies *need not* reside in only one existing industry, even though they *may*.

### Need to Incorporate the Role of Economic Actors in the Creation of a Radical Technology

While the literature on the nature of technology presents the above fruitful opportunities to address definitional issues arising from conceptualizing radical innovation based on economic effects, it is nonetheless silent on the role of economic actors *in its creation*, other than recognizing the need for experimentation (Rosenberg, 1992). In part, this is because of the level of analysis typically employed in technology studies, which is either at the technology or at the "economic system" level. For example, Rosenberg (1979) notes that the application of new technologies clarifies challenges and focuses innovative effort, and that many of the capabilities required to make a technology more useful often sit outside the bounds of a particular industry, he is silent on the micro-dynamics of who the economic actors are, what capabilities they draw upon, and how they build new capabilities and reconfigure existing ones to develop new technological systems. Similarly, while Arthur (2007) recognizes that individuals (within and across teams and organizations) to expend sustained and engaged effort in recursive problem-solving that arise in the creation and reconfiguration at both component and system level, he does not map these efforts to heterogeneity in economic actors vis-à-vis the capabilities they draw upon and their strategic positions in existing industries that utilize similar base principles to solve different purposes.

The process through which prior knowledge facilitates the iterative problem-solving process that generates new knowledge as building blocks for nascent industries harvesting a radical innovation has recently started to garner more attention in strategy and entrepreneurship. Here, recent work on incubation of industries and technologies has shown that the period between a technological discovery (invention) and first commercialization of a product embodying the radical technology is characterized by many firms with heterogeneous capabilities making investments to create a viable technology-use nexus (Moeen & Agarwal, 2017; Moeen, Agarwal & Shah, 2020). This research highlights that capabilities at the time of first commercial entry are not just based on prior knowledge contexts of the firms—startups and established firms alike—but are created through active experimentation and investments (Moeen, 2017), and vibrant markets for technology and corporate control (Moeen & Agarwal, 2017; Moeen & Mitchell, 2019).

In the context of our study, this highlights that the nature of the radical technology (as embodied in commercialized products in the new industry), at the end of the day, is determined by the economic actors that undertake development efforts to address fundamental uncertainty not only in the technology dimension, but also as the technology may interact with demand, ecosystem and institutional dimensions (Moeen et al., 2020).

### Research Questions and Conceptual Map

Based on the above premises, we can now turn to the research questions we examine in our study: How are radical technological systems created by economic actors that are heterogeneous in both their prior history and their experimentation efforts, and what implications does this have for their value capture strategies?

A radical technology—the creation of a system that uses new base principles towards a purpose—requires scholars to adopt an evolutionary lens where prior history is measured not at time of first commercialization, but at a time that precedes the creation of the radical technology.[8] Here, heterogeneity among economic actors may stem from their experiences in serving the focal purpose using existing technologies employing a base principle, serving a different purpose using sub-components relevant for the new base principles, or scientific discoveries and inventions related to new base principles.

During the "incubation stage" of the radical technology, the knowledge base is created through focused cognitive attention to recursive problem solving to create the new technological

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[8] Rosenberg's (1963) seminal treatment of the machine tool illustrates how machine tools evolved to serve a series of new industries from firearms to bicycles to automobiles, and how at first the machine tool industry emerged out of increased specialization in the creation of tools, and enabled and further co-evolved as these new markets were explored.

system—this requires identification and/or creation of both the sub-technologies that serve as components to the system, and of the interfaces and linkages that connect them into a working system. The pathways undertaken by economic actors during this stage of the process are shaped not only by their prior history, but also their active efforts in creating new knowledge and accessing knowledge created by others.

Given that making a radical technology useful requires the development of new supporting sub-technological systems, or the adaptation of existing ones, and/or integration, prior history and strategies for generating component and system level technological knowledge will then have implications for value capture strategies in the emerging industry that utilizes the radical innovation. Here, value capture strategies will additionally be shaped by complementary capabilities and ecosystem needs for profiting from innovation—some of the economic actors may choose to commercialize products based on the radical innovation (formally termed entrants in the emerging industries), others may choose to sell capabilities in markets for technology (formally termed alliance partners in upstream markets), and yet others may choose to transfer corporate control (formally termed acquirers and acquirees in mergers and acquisitions).

The above evolutionary process view enables the tying of the nature of a radical technology with its strategic causes and consequences, and thus consider how radical innovation might interact with firm capabilities and thereby affect industry structure and strategic positioning of economic actors.

## EMPIRICAL APPROACH

### Research Context: The Emergence of the Bionic Prosthetic Industry

Prosthetic limb devices are medical devices in orthopedics and physical medicine that are fitted to amputees in order to restore the lost functions of natural limbs. Prosthetic limbs are composed of various components such as the artificial ankle, foot, hip, knee, sockets, hook, wrist, elbow, shoulder, sockets, cable, and the prosthesis suction valve (US FDA 21 C.F.R § 890.3420, 2019). Similar to other medical devices, prosthetic manufacturers—the focal actor of the present study—develop, manufacture, and sell prosthetic products primarily to healthcare providers specialized in orthopedics and prosthetics ("O&P"), such as O&P clinics, hospitals, and surgical centers. O&P clinicians prescribe prosthetic devices based on their evaluation of patients' physical and mental conditions and need for mobility, subsequently ordering them and fitting amputees with the device in a clinical setting.[9] Figure 1 describes key actors and their roles in the prosthetic industry. Ultimately, prosthetic limbs exist to satisfy the end user's need for mobility. To meet this ultimate goal, prosthetic firms have focused on several important end-users' needs, including: (1) function—a prosthesis should be durable and improve the mobility of its user with greater controls over the device; (2) fitting—prosthetics should be wearable, less cumbersome and stiff; and (3) appearance—it is desirable that the prosthetic looks like a part of the natural human body and has a pleasing aesthetic.

[Figure 1 about here]

Bionic prostheses, also referred to as "robotic limbs," "robotic assistive technology," or "active prostheses," are cutting-edge devices first commercially introduced to the world in 1997. Arguably, one of the most significant technological advancements in prosthetic history (*The O&P Edge*, 2014), bionic prosthetics led to a surge of technologically sophisticated, new products in the O&P industry.[10] Distinctive features of bionic prostheses—compared to conventional mechanical

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[9] Fitting refers to the practice of connecting the device to a patient's body with a socket or any other suspension system and fitting components. Fitting involves the measurement, casting, alignment of the device, and follow-ups. Patients can opt for a cosmetic covering.

[10] For example, a pioneering firm in the bionic prosthetic market noted the rapid technological innovation and new product developments that were taking place in the prosthetic industry, reported that 50% of the firm's revenues were derived from new products during 1999 and 2001, in comparison to a 20% in 1997 (Össur's Annual Report, 2001).

prostheses—include electrically powered control systems, the interface between the residual limb and the device that provides sensory feedback, and technology that enables the devices to self-learn and adapt themselves to the user. The technological advancement was primarily enabled by the novel application of principles in electrical engineering, robotics, and neuroscience (hereinafter bionic prosthetic technology) (Burck et al, 2011; Ravitz et al., 2013).[11] For instance, sensing technology and microprocessors embedded in bionic limbs can perform more than a 1000 motion analyses and environment evaluations per second, and they also control the movement and speed of the bionic limb in real-time. Electrodes and targeted muscle innervation technology are designed to mimic the neural human-machine interface. The technology picks up electromyographic signals generated by the contraction of residual muscles or exchanges neural signals with the user's brain. As illustrated above, a bionic limb can adapt to the user's unique movements and even be controlled by the user's mind with sophisticated models. Radical electronics technology has empowered users of smart prosthetics with greater degrees of freedom in their limb movements and have enabled its users to engage in diverse activities such as climbing hills, running on uneven surfaces, and even delicate motions such as gripping and pinching. These series of movements would have been extremely difficult with traditional prosthetics.

Building bionic prosthetic limbs requires a technological system that hinges upon different sub-technologies—not only new bionic prosthetic technologies, but also old technologies that have accumulated within the conventional prosthetic industry. Material technology, product design, rehabilitation medicine, and clinical testing were traditionally critical for innovation, on which conventional firms had focused their R&D investments before the advent of bionic limbs. This includes the application of modular designs (e.g., tubes, pylons, valves) that increased interchangeability of parts and mechanical controls in the 1970s (Staros, 1979), C-shaped running

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[11] This novel approach is also referred to as biomechatronics.

blades conceptualized in the 1980s and popularized onward (*The New York Times*, 2008), and the utilization of lighter and durable materials, from wood and leather to more advanced materials, such as iron, aluminum, titanium, rubber, plastic, silicone, and carbon fiber composites. Also, precision manufacturing, marketing, and distribution remained as crucial for the commercialization of prosthetics. Table 1 displays key distinctions between the bionic limb system and the conventional limb system.

[Table 1 about here]

The duration of the incubation stage in the bionic prosthetic industry was approximately three decades, which makes it unexceptional relative to other industries (Agarwal & Bayus, 2002; Golder, Shacham, & Mitra, 2009; Moeen & Agarwal, 2017). Afterwards, a period of a sharp increase in sales occurred.

The concept of bionic prostheses emerged after World War II in an attempt to create an artificial hand with an automated grip function for wounded soldiers. However, at the time there was no way to fit automating technology into a sufficiently small form factor to be useful. This bottleneck remained in place until solid state electronics emerged in the 1960s and 1970s. Technological experiments and advancements began to accelerate, and academic researchers and firms continued research and development efforts throughout the 1980s and the 1990s. In 1997, the first commercial product of bionic limbs, the C-leg, marked the end of the long incubation period. The FDA approved the C-leg's commercialization in the U.S. market in 1999 (*The O&P Edge*, 2014). Figures 2 and 3 indicate technological investments and sales trends of bionic prosthetic limbs, respectively. Particularly, Figure 2 shows the growth trend of bionic prosthetic patents throughout the studied years, which approximates technological investments in bionic technology.[12] Figure 3

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[12] See Appendix for how bionic patents were identified.

depicts the growth of market sales based on Medicare Spending on bionic lower limb prostheses, indicating that the bionic prosthetic limb market has grown significantly since market inception.[13]

[Figures 2 and 3 about here]

### Research Design

The bionic prosthetic industry is a suitable context within which to examine our research question. First, the bionic prosthetic industry a novel problem-solution mix for mobility, fitting into our conceptual definition of nascent industries. Second, bionic prosthetic products are "radical", in that they rely on a new base principle. Third, this context allows us to observe relevant actors, their capability development processes, and their eventual commercialization strategies, as well as triangulate across rich quantitative and qualitative historical data from multiple data sources.

We adopt a historical approach. Historical methods are qualified eminently to study the evolution of nascent industries, firm capabilities, and entrepreneurial processes (Forbes & Kirsch, 2011; Lippmann & Aldrich, 2014; Jones & Wadhwani, 2014). Firm histories unveil path-dependent processes of building capability through sequential historical events and allow an in-depth examination of the underlying variation, selection, and retention processes intertwined between firm actions and opportunities' conditions (Lippman & Aldrich, 2014). We systematically create firm and industry histories along with the emergence of bionic prostheses by triangulating across quantitative data on 102 firms during the industry's incubation period (1975-1997) and the takeoff period (1997-2014) and historical narratives for 15 selected sample firms. Our quantitative data examine the key relationship of interest. Then, our historical data capture important factors which my quantitative

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[13] The majority of prosthetic devices are paid for by public and private healthcare insurers, similar to other medical devices and healthcare services. Medicare spending is an important index for sales and growth trends, widely accepted by various participants in the O&P field. Medicare covers approximately 30% of the medical payments for prostheses and sets standards of reimbursement for private insurers. Lower limb prostheses account for approximately 90% of the market demand, thus being reasonably representative of the growth of market sales. A caveat is that the beneficiaries of Medicare are people who are over 65 years old, so this data may be underestimating the gross sales of bionic prostheses by omitting younger prosthetic users who tend to be much more active and more eligible for high-functioning devices.

data do not measure, essentially providing the most plausible explanations at play. In other words, our approach to infer results is abductive (Heckman & Singer, 2017; King, Goldfarb, & Simcoe, 2019; See empirical examples in Agarwal, Braguinsky, & Ohyama, 2018; Goldfarb & Kirsch, 2020; Kim, 2020; Pillai, Goldfarb, & Kirsch, 2020).

Ultimately, we attempt to map the entire technology chain—the entire set of sub-technologies necessary to deliver bionic prosthetics to patients—onto firm capabilities, and examine which firms, enabled by the new principles underlying radical technology, were capable of creating the pieces of a new system or assembly, and which of those firms actually undertook the creation of the pieces of the new, radical, bionic system or assembly. We then use this information to consider the how a firm's technological positioning interacted with existing strategic resources, such as access to customers, or complementary parts of the technological system.

### Sample and Data

We compiled a unique and novel database for the nascent period of the industry. We triangulated information from multiple historical data and archival sources (Forbes & Kirsch, 2011) in order to identify the relevant actors who collectively drove the market emergence, as well as to demonstrate a full understanding of the sequence of their actions and outcomes (Forbes & Kirsch, 2011; Santos & Eisenhardt, 2009; Wadhwani & Jones, 2014). Table 2 describes key constructs, operationalization, and relevant data sources.

In this context, the nascent period is defined as the period between 1975-2018. We empirically define the inception of the incubation period as the year 1975, when new electronics capabilities inspired the first bionic prosthetics patent that was filed by a firm and which appears in our dataset. The starting point of the commercialization period is marked as the year 1997, when the world's first bionic limb was commercialized.

We construct a sample of "technology-investing firms," which refers to the firms that engaged in technological investments in bionic prosthetic limbs, representative of the firms who created the technological base of the bionic prosthetic limb industry. Technological investments are captured by not only the internal, but also the external R&D efforts made by firms over the sample period.

Firms' internal R&D investments are measured by clinical trials and patenting activities, which have immediate applications for creating prosthetic limb components and integrated products.[14] [15] Using the Fung Institute Patent Data and the PatentsView database, we identify prosthetic patents and pending patent applications that rely upon "new" principles embedded in smart prosthetics, such as sensors and electrodes, microprocessors, data processing and artificial intelligence, and electrical sources of power.[16] We develop search algorithms based on both technology classifications specific to prosthetic limbs as well as the textual information of patents. The keywords used in the search queries were shortlisted by looking into influential trade journals and major prosthetic firms' websites. In order to ensure the validity of our search strategy, we consult with two patent analytic firms. We also perform thorough manual reviews with the firms to minimize false negatives and false positives in the outcome. Lastly, we restrict the *technological investment by patenting* to the patent records that are cited by at least one granted patent filed in the relevant prosthetic limb technological subclasses.[17]

Firms' external R&D investments are measured by acquisitions and alliances, using the SDC Platinum database using relevant SIC codes—"3841 (Orthopedic, Prosthetic, and Surgical

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[14] Patenting accounts for the majority of the captured internal R&Ds.

[15] Patents are a proper proxy for technological investment in this research context; the majority of the firms operating in O&P filed a number of patents to protect their products, including bionic technology (Ossur Annual Report, 2006), and use patents as an indicator of their R&D investment.

16 The details of the patent search strategy are attached in the Appendix.

17 The unrestricted sample yields consistent results. Pending applications were manually investigated whether citing firms included prosthetic firms due to limited availability of structured data.

Appliances and supplies)" and "3845 (Electromedical and Electrotherapeutic Apparatus)"—as well as industry news published in trade magazines. We also search for events where firms acquired or allied with other technological investing firms by using patent assignment, corporate websites, annual reports, and Nexis Uni.[18] When a focal firm acquired another firm that invested in bionic prosthetic technology or a relevant business division, the firm is identified as a technology investing firm by acquisition. Also, the firm is identified as a technology investing firm by alliance when the firm engaged in technological alliance with other firms or research institutes with regard to bionic prosthetic technology. Together, this data collection and cataloging process on various types of technological investments allowed for the approximation of a comprehensive technological space for the bionic prosthetic device industry during its emergence.

Our sample consists of 102 firms that engaged in experimentation efforts for the creation and reconfiguration of relevant bionic prosthetic sub-components and their integration and assembly into systems. We rely on the most widely used definition for firm types (Sosa, 2013) to facilitate the comparison of the results with previous studies. We define incumbent prosthetic firms as the firms who produced any prosthetic limbs, components, or accessories before initial technological entry. Other established firms are the firms who were in other industries before initial technological entry. Startups are the firms who had no business histories in other industries before its initial technological entry. These technology-investing firms include 20 incumbent prosthetic manufacturers, 52 established firms that had operated in other industries, and 30 startups. It is worthwhile noting that some of the firms engaged in compound strategies to acquire subtechnological systems as the mean of technological investments is 1.48 (Std. Dev: 1.48) and used up to three different diverse modes of technological investments over the sample period, such as internal R&Ds, alliances, and acquisitions (Mean: 1.10, Std. Dev: 0.37). This indicates that firms in

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[18] Lexis Uni was formerly called Lexis Nexis Academic.

nascent industries may utilize various strategies to build out capabilities to implement radical subtechnological solutions. For the firms that are associated with multiple instances of technological investments, the firm's technological entry was recorded by its first technological investment. Our historical analysis supports this interpretation, suggesting and further suggests that this strategic heterogeneity can be tied to pre-entry technological capabilities.

[Table 2 about here]

### Analyses on who created the technology base of the bionic prosthetic limb industry

We begin with descriptive statistics on firms' technological entry in the nascent period, as well as relevant firm-level characteristics. Figure 4 depicts the number of new companies that invested in bionic limb technology during the emergence of the industry. Figure 5 aggregates the number of new investing firms shown in Figure 4. This figure describes the share of firm contributions to the technology base of bionic limb technology among different groups of firms, aggregated over time. Figures 4 and 5 indicate that various firms invested in bionic technology, including incumbent firms, established firms from other industries, and new ventures, consistent with previous studies (Cattani, 2005; Moeen & Agarwal, 2017). Interestingly, established companies in other industries, such as other healthcare sectors, electronics, and automobile industries, actively contributed to the development of the technological base from the beginning. Established firms from other related industries had the highest share in technological investments across time (Figure 5).

[Figures 4 and 5 about here]

### Analyses on differing paths to the value capture

The firms that possessed new technological capabilities pursued different paths in order to capture profits within the focal industry. Figures 6a, 6b, and 6c depict Kaplan-Meier survival curves on the estimated time to the eventual value capture event by firm type. The firms at risk of engaging in a value capture activity consist of technology investing firms during incubation and takeoff. First, taking a look at the acquisition events (Figure 6a), the estimated hazard rate of startups being acquired is the highest compared to incumbent prosthetic manufacturers and established firms from other industries.

[Figures 6a, b, and c about here]

Table 3 summarizes the number of technological investing firms at risk of engaging in a value capture event, as well as their eventual value capture events. The descriptive statistics of Table 3 are consistent with the pattern in the Kaplan-Meier curves. Conditional on technological investment, both incumbent prosthetic manufacturers and startups engaged in various forms of value capture activities within the prosthetic industry, which is in stark contrast with established firms from other industries. 6 out of 52 (11.5%) established firms from other industries in the sample either entered the product market or captured the value from market mechanisms such as acquisitions and technological licensing. In contrast, 11 out of 20 (55%) conventional prosthetic manufacturers, and 12 out of 30 technology investing startups (40%), are associated with value capture activities within the focal industry. Incumbent prosthetic manufacturers and startups also markedly differed in terms of their eventual choice of the value capture. First and foremost, incumbent firms were the most salient providers of radical bionic prosthetic systems. 9 out of 20 technology investing prosthetic manufacturers chose to enter the prosthetic limb market as their eventual path to the value capture, and this accounts for 60% of firms that entered the bionic prosthetic limb market. On the other hand, startups were most likely to value capture through market mechanisms. 11 out of 30 startups were eventually acquired, which account for 61% of value capture activities through acquisitions in the nascent period of the focal industry. 8 out of 30 startups were engaged in technology licensing or the sales of their patented knowledge, and 5 of them were eventually acquired. 8 startups launched bionic prosthetic limb products, but 5 of them were eventually acquired. 3 out of 30 (10%) startups are associated with market entry into the bionic limb market as their eventual choice of the value capture.[19]

[Table 3 about here]

## HISTORICAL ANALYSIS ON DIFFERENT PATHS TO RECONFIGURATION AND VALUE CAPTURE

How and why did different firms chose different paths from technological investment to value capture in the face of a radical technology? Business histories provide unique opportunities to unveil path-dependent factors that condition organizational outcomes through time and investigate the evolution of firms and new industries (Forbes & Kirsch, 2011; Lippmann & Aldrich, 2014; Wadhwani & Jones, 2014). Using the "historically significant" (Chandler, 1977; Kipping, Wadhwani, & Bucheli, 2014) business histories of 15 technology investing firms, we illustrate the processes of capability acquisitions and organizational outcomes across diverse firm types. Selection criteria were as follows. In this context, we define historically significant cases by the firms' contributions to the industry's technology base (top 15%), rather than by their eventual economic outcomes (c.f., Lippmann & Aldrich, 2014).[20] Employing the idea of stratified sampling, we select 5 salient technology investing firms from each firm type by count of knowledge acquisition activities. We exclude ambiguous cases in which the firm had prior experience producing conventional prosthetics, but exited the market before its technological entry, for stark comparisons. When the count of knowledge acquisitions is on par, we prioritized the cases involving acquisitions and alliances over patenting; otherwise, the cases were selected randomly. These 15 firms are historically significant and comparable regarding their "new" technological capabilities. Hence, they offer comprehensive explanations on the variation and processes of capability development that were necessary to deliver

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[19] The findings are corroborated with business histories and linear probability models on the firm's probability of entering the nascent market.

[20] It is a right-skewed distribution.

an assembly of bionic prostheses. The data on firm business histories come from press releases, annual reports and materials for investor relations (if public firms), industry analyses, news articles, searches on Nexis Uni, corporate websites, trade magazines, and other relevant sources (e.g., academic journals).[21]

Our historical analysis generated several important findings that bring nuance to the previous literature. Figure 7 represented the developmental process. First, incumbent firms, startups, and established firms from other industries took differing paths from technological entry to the value capture, conditioned by what pre-existing capabilities they had and how their capabilities fit with the nature of the changes in the bionic prosthetic system. Firm business histories suggest that the existing capabilities of incumbent firms, inherited from the conventional prosthetic industry, complemented the new bionic technology, rather than becoming obsolete. This includes not only downstream capabilities such as marketing and sales, but also upstream technological capabilities that were necessary for product development and designs. Thus, conventional prosthetic manufacturers were well positioned to integrate bionic prosthetic systems into a complete prosthetic solution than other types of firms. Importantly, incumbent firms leveraged material and general prosthetics knowhow to improve existing subtechnological solutions used in, and thus improve the complementarities between existing solutions and radical solutions offered by the new bionic technology. The results indicate that radical bionic limb technology did not automatically create the obsolescence of incumbent firms' existing capabilities. Relatedly, our findings illuminate the process through which the emergence of a nascent industry may ensue from technological convergence. That is, some radical technological systems, such as bionic prostheses, may stem from the convergence of previously distant old and new technologies, respectively changing in flux. Second, some of the established firms from other industries attempted to integrate their bionic capabilities

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[21] See Table A2 in the Appendix for detail.

into other technological systems *outside* of offering bionic prosthetics. This observation engenders both industry-level and firm-level implications, indicating that the emergence of the bionic prosthetic industry was significantly affected by knowledge spillovers from firms developing applications in adjacent areas, such as wearable robotic devices. Also, these "spillover" firms developed technological systems in adjacent industries, a parallel world where conventional prosthetic manufacturers may be defined as established firms from other industries. The spillover firms attempted to leverage their "existing" capabilities in adjacent industries.

[Figure 7 about here]

Table 4 summarizes some of the distinctive patterns observed in the firms' business histories. This includes the stock and flow of firm capabilities in relation to old (conventional prosthetics) and new (bionic) technology, as well as the firm's value capture events within the prosthetic market in the forms of market entry, licensing, and acquisitions. The historical analysis confirms the quantitative finding that incumbent firms were the most salient providers of the radical bionic prosthetics system than other types within this context, consistent with the quantitative analysis. Moreover, the incumbent firms introduced more product lines (average 5 products) than other types (average 1 product), conditional on market entry.

[Insert Table 4 about here]

### Firm capabilities prior to technology entry

While incumbent prosthetic firms possessed upstream and downstream capabilities related to "old" prosthetic technology, and lacked capabilities related to bionic technology (e.g., electronics, robots) prior to their initial investment in bionic technology, startups and other established firms possessed upstream capabilities related to "new" bionic technology before technology entry. Specifically, all four incumbent firms possessed upstream capabilities in material science, rehabilitation medicine, and mechanical product designs, traditionally important to mechanic prosthetics. The incumbent firms focused on "lightweight, energy storing prosthetic devices" with new materials and designs, including a "carbon fiber prosthetic system using materials developed for the aircraft industry" and "modular design." They also possessed downstream capabilities, such as marketing, sales, and manufacturing, for orthotic and prosthetic devices. Also, these firms were not diversified, but rather specialized in orthotics and prosthetics, similar to the majority of other firms in the prosthetic industry. In the meantime, three of the startups were university spin-offs with research experience in new bionic technology. One startup was co-founded by an amputee lawyer who was a long-term patient of an advanced prosthetic lab and two academics with expertise in bioengineering and prosthetics. Among the four, another startup's founder had an experience of engaging in technology transfer to a technology investing prosthetic manufacturer. All of the startups had no experience related to manufacturing, marketing, or sales in prosthetics at the time of technological entry. Lastly, the primary businesses of other established firms include automobile manufacturing, electronics, steel and machinery, and technology services. These established firms from other industries had upstream capabilities in electrical engineering, computers, and/or robots, and downstream capabilities obtained from their previous business experience in automobiles, electronics, and steel.

### Acquisition of new bionic technology

Across different firm types, all technology investing firms made substantial efforts to obtain technological capabilities in new bionic technology through various modes of capability building. Although this is a similar developmental focus, different types of firms have built their technical capabilities on bionic technology in systematically different ways, guided by their pre-existing capabilities before technological entry. A notable difference is observed with regard to their various patterns of utilizing business acquisitions. While the conventional prosthetic firms continued to acquire firms that possessed bionic prosthetic technology throughout time, the startups' business acquisitions were focused on the initial phase of the firm's founding. Also, the startups were more focused on a product line, while incumbent firms extended their investments on multiple product lines. Contrary to other types, established firms did not engage in any acquisition of firms or business divisions in the area of bionic technology.

Conventional prosthetic manufacturers were the most salient group of firms that acquired bionic-related technology. All of these firms acquired knowledge not only through internal development, but also through acquisitions and R&D alliances with universities, startups, and other established firms. For example, Otto Bock began to experiment with the concept of powered limbs from at least the 1960s by partnering with other medical device firms who possessed knowledge in electronics (Childress, 1985). The firm's R&D efforts came to fruition as the world's first commercial bionic prosthetic knee in 1997. This outcome was fostered by the firm's acquisition of a bionic prosthetic patent in 1992 from a university spinoff who was seeking to sell its bionic leg technology in a tradeshow. The deal was followed by more than four years of extensive R&D cooperation between Otto Bock and the startup. Otto Bock competitor Össur also acquired new bionic technology in a combination of in-house R&D, R&D alliances, and acquisitions. The firm began to engage in a long-term R&D project and technology licensing with MIT around 2000, which led to the firm's first bionic limb device, the Rheo knee. Also, Ohio Willow Wood entered the technological space through R&D alliances with research labs in 1999, by offering its expertise in conventional prosthetics. Blatchford engaged in R&D collaboration with research labs (e.g., the U.K.'s National Health Service) and licensed bionic prosthetic technology from Kobe Steel, an established firm that invested in bionic prosthetic technology. Two of the firms utilized both R&D alliances with and acquisitions of various organizations with bionic prosthetic technology throughout time, including startups, established firms in prosthetics, as well as other industries. The other two firms leveraged market mechanisms, focusing on R&D alliances with technology investing firms (a startup and an established firm from other industries) and research institutions.

Startups played a critical role in transferring cutting-edge university research into the new industry. Startups acquired their capabilities in new prosthetic technology primarily by building upon the founder's knowledge in bionic prosthetic technology being developed at universities. For instance, one startup's founder noted, "In 1997, I realized that artificial intelligence could be applied to something like a bionic leg." Moreover, these startups leveraged market mechanisms to acquire bionic technology. All startups licensed technology from the universities with which their founder was affiliated (3 firms) at its founding, or a research institution in an R&D alliance (1 firm) in its early years of the firm's establishment. Two of the technology investing startups acquired other startups already in possession of the bionic prosthetic technology at the firm's founding, or within a year of the firm's founding.

It is helpful to see how the acquisitions facilitated the grafting of new radical subsystems into the technology that was prosthetic limbs. By leveraging capabilities in machine controls, Kobe Steel entered a research partnership with the Hyogo rehabilitation center to apply the microprocessor control to the prosthetic knee in 1989. The firm granted a patent which was later licensed to an incumbent company, and which greatly impacted follow-up inventions in bionic prosthetics. Similarly, some firms entered the market primarily motivated by the technological potential of bionic technology. Honda Automobile began research and development on bionic technology in 1999, with the broad aim of providing cutting-edge technology for human mobility assistance, rather than with a laser-focus on prosthetic applications. The firm was primarily motivated by the potential applicability of its pre-existing upstream capabilities, such as applying the control system and sensors for human walking, originally developed from the automobile business and the firm's humanoid robot project, ASIMO. Notably, not all firms entered the technological space deliberately. Instead of proactively seeking the opportunity, DEKA Research & Development Corp was sought after by the Defense Advanced Research Project Agency (DARPA) in order to develop a bionic prosthetic arm for wounded veterans. In DEKA's case, DARPA set the desired technological specifications and delivery time for the firm, and led by organizing the entire development processes. The founder/CEO of DEKA described the idiosyncratic interaction with DARPA that ultimately led the firm's technological entry as follows: "The very first time we met with DARPA, and they described, 'We want an arm that can do this and this and this and this and this,' we told them, 'You're nuts'... 'because the technology is not there" (CNN Newsroom, 2009). Nonetheless, it is evident that DEKA's pre-existing upstream capabilities in electronics attracted DARPA's attention, opening up the opportunity for its technological entry to bionic technology.

Historical record indicates that all of the established firms leveraged R&D alliances in the capability development, along with internal research, exemplified in the following remark: "During the year, we announced a new brain-machine interface creating basic technology for manipulating robots using human brain activity as a result of joint research with Advanced Telecommunications Research Institute International" (Honda Annual Report, 2007). However, the established firms showed the lowest level of engagement in business acquisitions than the other types of firms.

### Acquisition of old prosthetic technology

Conventional prosthetic manufacturers, startups, and established firms from other industries differ significantly in their building capability of old prosthetic technology. Conventional prosthetic firms were the most active actors in acquiring both conventional prosthetic technologies that were required for product design (upstream) and distribution channels, precision manufacturing, and marketing in order to market the developed products (downstream). Specifically, three of the incumbent companies invested in upstream capabilities for better product design, such as advanced carbon composite materials and hydraulic technology. In renewing the old technology, the conventional prosthetic firms allied with and/or acquired other orthotic and prosthetic firms throughout the study period.

In contrast, both startups and established firms' investment in conventional prosthetic technology was sparse. Some startups extended an effort to access talent acquisition in sales and entered a distribution agreement with existing prosthetic companies. Some of the established firms from other industries and startups allied with hospitals for the clinical testing of their prototype technologies, as well as with existing prosthetic firms, in order to license their bionic technology. However, their developmental effort to advance conventional prosthetic technology, such as materials or fitting, was largely limited. Moreover, none of the startups and established companies dedicated their resources to acquiring firms or business units that possessed conventional prosthetic technology, neither upstream technology for product design nor marketing and sales.

Incumbent firms did not only invest in old prosthetic technology for their existing conventional prosthetic businesses. They had a clear strategic focus in capability development, which is the integration of their existing capabilities in old prosthetics with new bionic technology. This is exemplified by a remark of an incumbent firm from the conventional prosthetic industry, noting, "By the innovative application of its core technologies, materials knowledge and sales and marketing expertise, Össur intends to move forward into new business areas in the future" (Össur Annual Report, 2002).

As noted in the prior research context section, existing prosthetic technology in material science, mechanical engineering, and clinical testing experience remained useful in the product design of bionic prosthetics. Also, knowledge related to fitting and customer education helped to increase the effectiveness of the device. For instance, the carbon fiber technology has remained crucial in the prosthetic industry ever since the 1990s for its beneficial properties of being lightweight, having the ability to store energy, and strong durability (Klasson, 1995; *The O&P Edge*, 2006). Also, the existing technology of mechanical control (e.g., hydraulic and pneumatic) remained valuable, especially when being combined with microprocessor controls. In addition to the first-order effect of the existing technology's functional utility, the existing prosthetic technology helped to manage the tradeoffs between new functions and usefulness in the integration of newer components. A startup noted "the convergence of bionics and prosthetics" as a critical mechanism with which to facilitate "the development of technologies that will greatly enhance mobility, energy efficiency and gait patterns" (Victhom Human Bionics Inc, 2005). Relatedly, a researcher with approximately 18 years of experience in bionic prosthetic technology emphasized both the importance and the difficulty of the reliability of the novel devices based on bionic technology, by noting: "…these things, in the laboratory, we go for increased sophistication, but that, kind of, necessarily hurts the reliability…bringing the usefulness and the functions together is an outstanding work."[22] These remarks highlight a second-order effect of existing technology, in that existing technologies may help firms to manage the tradeoffs between new functions and usefulness during the integration of newer technology. Clinical trials can provide user-cited reliability and comfort (Burck, Bigelow, & Harshbarger, 2011), which is also useful to prove the effectiveness of the device to the health insurance payers. Clinical education maximizes the outcomes of the patients and facilitates the reimbursement process (*The O&P Edge*, 2017).

Interestingly, some of the crucial existing technology was not the mere stock of the available knowledge, but rather have constantly evolved alongside bionic technology. Table A3 in the Appendix displays the evidence on firm actions associated with the investment in and the utilization of existing technology. Fitting technology, including sockets that connect the body and to the device, has been constantly innovated in terms of materials, structures, and fabrication methods (*The O&P Edge*, 2006). Prosthetic manufacturers kept investing in material science and engineering in

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[22] Source: an open-ended in-depth interview conducted by the author in 2018.

search of lighter, more resilient, and more robust materials, as well as the better utilization of existing materials, including carbon fiber.

[Insert Table 6 about here]

### Differing paths to capability building and outcomes

In summary, incumbent prosthetic manufacturers, startups, and established firms from other industries have pursued differing paths of developing capabilities related to old and new technology during the emergence of the bionic prosthetic industry, engendering a variety of different organizational outcomes.

Conventional prosthetic manufacturers played the significant role of integrating old and new technology within the firm and entering the nascent product market most actively. After market entry, the conventional prosthetic firms, on average, brought in the greatest number of products to the market. Conventional prosthetic firms took the path of investing in old and new technologies simultaneously, and these firms made significant investments in new bionic technology, no less than other types of firms. Also, the firms invested in old technology by leveraging the stock of their existing capabilities in old prosthetic technology and further advancing their conventional technology in order to accommodate technological tradeoffs coming from the incorporation of new technology (e.g., the increase in weights and the reliability issue with complex structures and operating mechanisms). Also, the user's needs for comfortable fitting never diminished, but rather became even greater, keeping fitting technology and clinical studies critical. Fundamentally, the incumbent's primary mode of value capture through market entry was made possible because of the nature of technical change. The evolution of bionic prosthetics ensued because of the convergence of old and new technology, powered by interdisciplinary research and the development of old and new disciplines, including rehabilitation medicine, material science, neuroscience, physics, electrical engineering, and mechanical engineering, rather than obliterating conventional prosthetic technology. Conventional prosthetic manufacturers were better positioned to integrate the new radical technological system in this type of technical change.

The bionic capabilities of the startups were largely integrated into conventional prosthetic firms. Two of the startups licensed their bionic technology to conventional prosthetic firms, and three out of the four startups were eventually acquired by conventional prosthetic manufacturers. Startups took the path of focusing on providing new technology hinged on cutting-edge university research. Startups advanced the founder's research, licensed from research institutions, and acquired other academic startups in order to build capabilities regarding bionic technology. However, their effort to update conventional prosthetic technology was limited and passive, compared to that of conventional prosthetic firms. Their bionic capabilities eventually converged into conventional prosthetic companies through licensing and acquisition.

Some of the established firms from other industries took an interesting path to value capture other than licensing, acquisition, or market entry to the bionic prosthetics, largely distinct from other groups of firms. Two of the firms grounded in automobiles and electronics entered an alternative downstream market of robotic wearable devices for medical and industrial purposes, and these choices were shaped by their pre-existing capabilities. Regardless of the differing paths toward value capture, all of the established firms created a significant amount of knowledge spillover from adjacent industries, which were previously distant from the conventional prosthetic industry.

As one could expect, there were variants that deviated from the statistical findings. Not only did incumbent prosthetic manufacturers enter the market, but also other types of firms did so as well. An MIT spinoff called iWalk entered the bionic prosthetic market through distribution agreements with existing firms. However, the firm was eventually acquired by a technology investing prosthetic manufacturer during the nascent period. Some firms, including a startup and an incumbent firm, launched various components of smart fitting systems that would complement both bionic and conventional prosthetic limb devices. An established firm from other industries, DEKA Research & Development, also entered the bionic product market. In this anomaly, DEKA had privileged access to both old and new prosthetic technology through DARPA's careful organization of research, development, and clinical testing processes, as well as the selection of various participating firms and universities that formed the basis for the integration of old and new prosthetic technology. This coordinated development extended the commercialization process as well, subsequently enabling the firm's entry into the bionic prosthetic market. A firm called Mobius Bionics was established to manufacture and distribute DEKA arms (Burck et al, 2011; McLoughlin, 2009; *The O&P Edge*, 2009). However, the majority of the cases are largely consistent with the statistical finding.

## DISCUSSION & CONCLUSION

The descriptive statistics, estimated models, and qualitative evidence all provide intriguing insights about the reconfiguration process of heterogeneous actors in an emerging industry, as well as its eventual economic implications on firms and ensuing industry structures.

Various types of value capture strategies were observed within the bionic prosthetic industry, including commercialization, acquisition, and the market for technology. Our results indicate that incumbent firms in the bionic prosthetic limb market did not fall behind in their technological investments, and that radical technology does not always necessarily make existing technologies obsolete. The capability development of conventional prosthetic manufacturers was conducive to the convergence of old and new technology, as well as the introduction of a variety of bionic prosthetic products. Startups infused the new industry with cutting-edge technology developed in research institutions, subsequently trading with and integrating into the conventional prosthetic manufacturers. Established firms induced knowledge spillover from formerly distant industries.

Some of the firms pursued a distinctive mode of value capture by entering an alternative nascent market, instead of entering or trading within the bionic prosthetic market.

This study is not without limitations, and the results should be interpreted with several caveats in mind. First, quantitative data on technological investments focus on the firm's capability, while not fully capturing potentially differing strategic intentions of firms at the time of investment. Business histories partly address this issue by illustrating how some firms in the same group—who entered the technological space with differing motivations or expectations about the potential use and value of their investment (e.g., Henderson, 1993)—achieved similar outcomes when undergoing similar processes of capability development. When and how cognitive aspects interact with the capability development should be further investigated in order to broaden our understanding. Also, our paper does not claim that investing in old technology, nor certain modes of value capture (i.e., market entry), are superior and dominant strategies. Rather, we highlight certain conditions under which investing in existing technology is complementary and essential to commercializing new technology. Also, this study uses a particular context that features various industry-specific factors, and this could impede the generalizability of the findings. For instance, some of the demand conditions of the studied industry (e.g., the size of the amputee population) may be less uncertain than those of other nascent industries. While this feature may be helpful in ruling out alternative explanations to the observed outcomes, the results should be interpreted by carefully considering idiosyncratic contextual factors.

By employing the technological system view, this essay challenges the circularity in the definition of radical technology and its eventual impact on firm capabilities. This forward-looking approach engenders interesting and important insights, contributing to the literature on competitive dynamics between incumbent firms and new entrants. Prior research often implicitly assumes that existing technological principles become obsolete or are stagnant in the advent of new technology, but we found evidence from historical record demonstrating that old technology principles, including prosthetic materials and designs, have consistently evolved, which may be conducive to the emergence of a new industry. Capabilities created in the obsolescing industry may provide an advantage in integrating technological components into a useful, novel solution (product R&D), and delivering it to the end users (commercialization) in nascent industries, thereby influencing a firm's value capture strategies. Also, our study deepens our current understanding of incumbent firms' advantage in nascent industries. Prior studies largely focus on the buffer effect of old "downstream" technology, which may enable incumbent firms to pioneer the nascent market (Mitchell, 1989) and to appropriate value from their technological capabilities (Tripsas, 1997). Our findings suggest that old "upstream" technology may be instrumental to the product design of radical technological systems in addition to efficient manufacturing and sales. These important findings showcase the fact that the strategic implication of radical technology can be better understood by applying the nature of technological systems (Goldfarb & Kirsch, 2020).

Furthermore, our findings support and extend the notion of "entrepreneurship in the large corporation" (Ahuja & Lampert, 2001; Katila & Ahuja, 2002), as well as "recombinant capabilities" (Fleming, 2001; Yayavaram & Ahuja, 2008). The literature on incumbent-led innovation abstracts away from the industry lifecycle aspects. Similarly, the studies on "recombinant capabilities" are silent about important factors such as the economic actors' characteristics (i.e., only examining technology level factors), as well as when the recombination of old technologies matters. In this paper, we connect the literature to the macro-level conditions under which entrepreneurship in the large corporation may become salient, and also confirm that the recombination of old and new technology is useful, by highlighting the nature of technical change and focusing on the nascent period of the industry.

Lastly, our paper extends the understanding of the configuration of firm capabilities on general upstream resources with implications for the firm's value capture strategies. Our historical analysis indicates that a firm's choice of trading in or entering a market depends not only on the presence or lack of downstream capabilities within a single focal market (Conti, Gambardella, & Novelli, 2019), but also the presence or lack of downstream capabilities in alternative markets as well. The relative strength across alternative downstream markets would play a substantial role in shaping the firm's value capture decisions. In addition, the firm's investment in generalizability (i.e., maintaining the technology as either general or tailored more toward a certain market) may be dependent not only on the demand conditions, including potential opportunities to trade the technology and the size of the downstream market (Conti et al., 2019), but also on the absolute and relative cost of acquiring complementary upstream capabilities (e.g., old upstream prosthetic technology, in our research context). This aspect may be of particular importance when the process of creating a market-specific application involves the technological convergence (Rosenberg, 1963) of various technology evolving simultaneously, as well as interdisciplinary research, which may not be uncommon in the application of general technology. Finally, our findings connect the configuration of general technology and market entry in relation to the Rosenbergian view on the diffusion of general-purpose technology.

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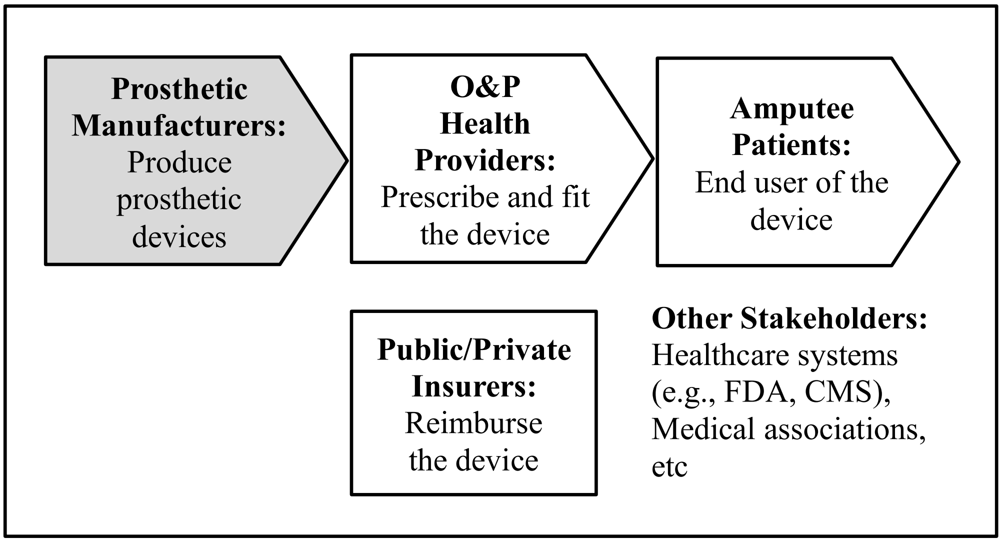
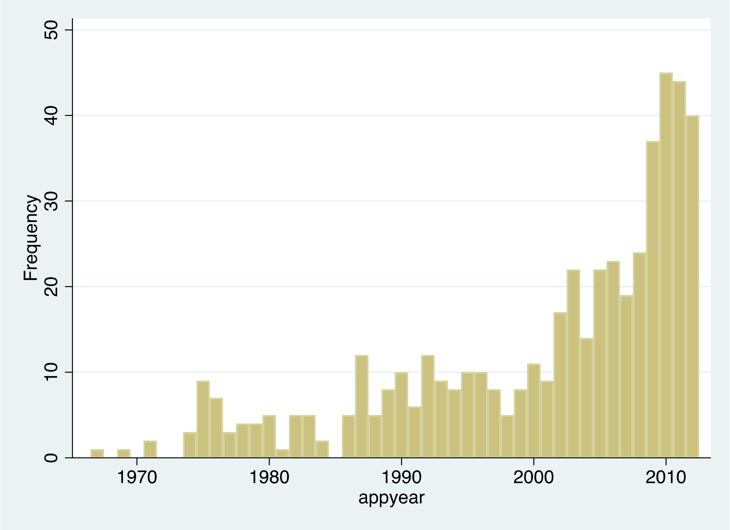
## FIGURES AND TABLES

### Figure 1: Key actors in the prosthetic limb industry

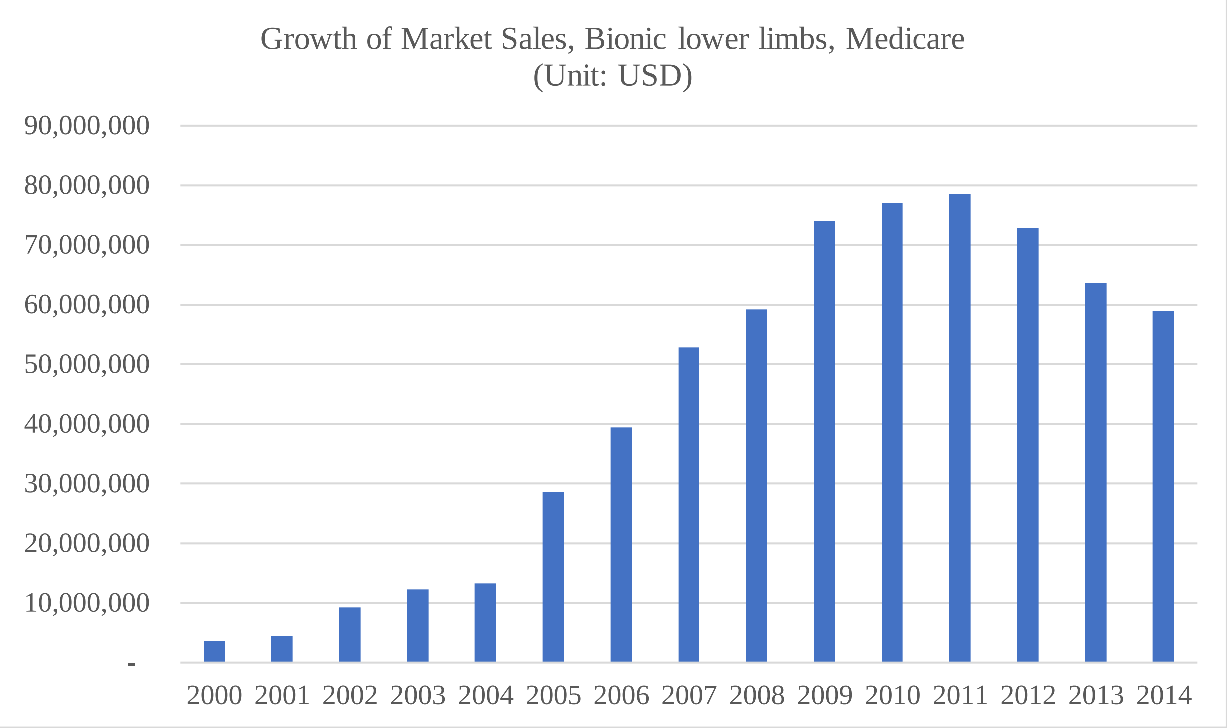


### Figure 2: Count of Bionic Prosthetic Patents, by Application year, USPTO



(Note: The figure represents the entirety of patented bionic prosthetic technology. The applicants of the patents include various actors, including firms, non-profit organizations, government agency, and individuals.)

**Figure 3: The growth of Medicare's spending on bionic limbs**



(Note. Medicare spending on the bionic lower limb (Source: www.cms.gov). The decrease in Medicare spending since 2011 was not caused by the contraction of the market demand but by the Medicare's stringent audit on medical device reimbursement. Note that the global prosthetic market is estimated as USD 1.3-1.4 billion as of 2019 according to Össur Annual Report (2019))

**Figure 4: The number of firms investing in bionic technology, by initial investment type**

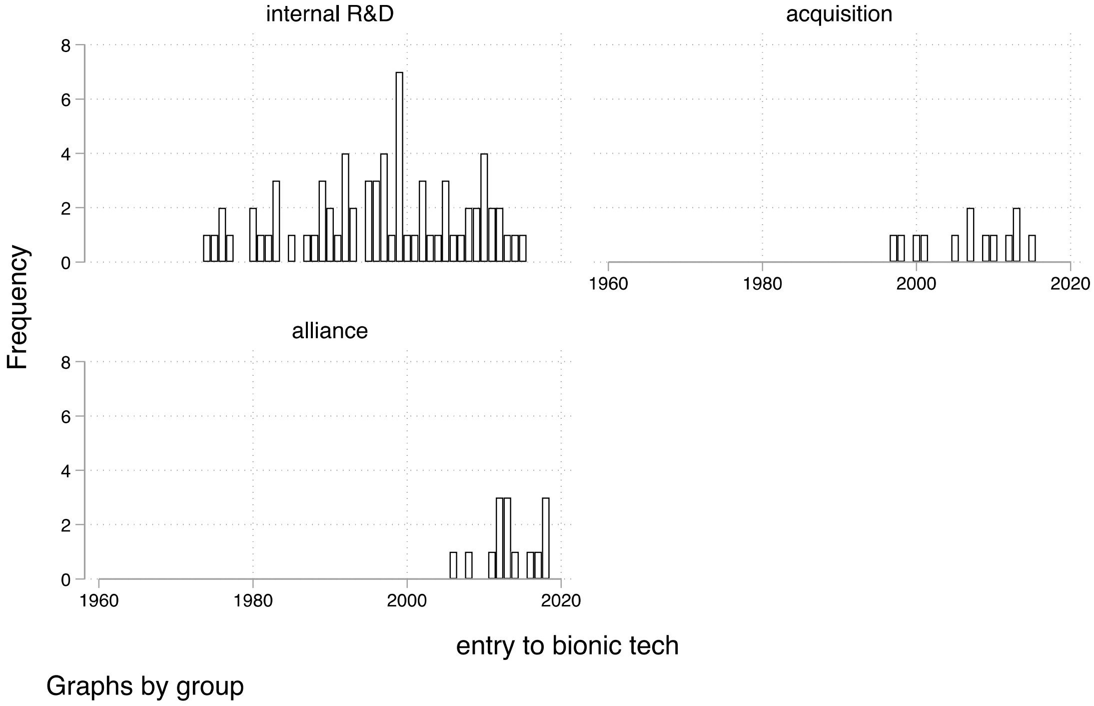


**Figure 5a: The number of firms investing in bionic technology, by firm type**

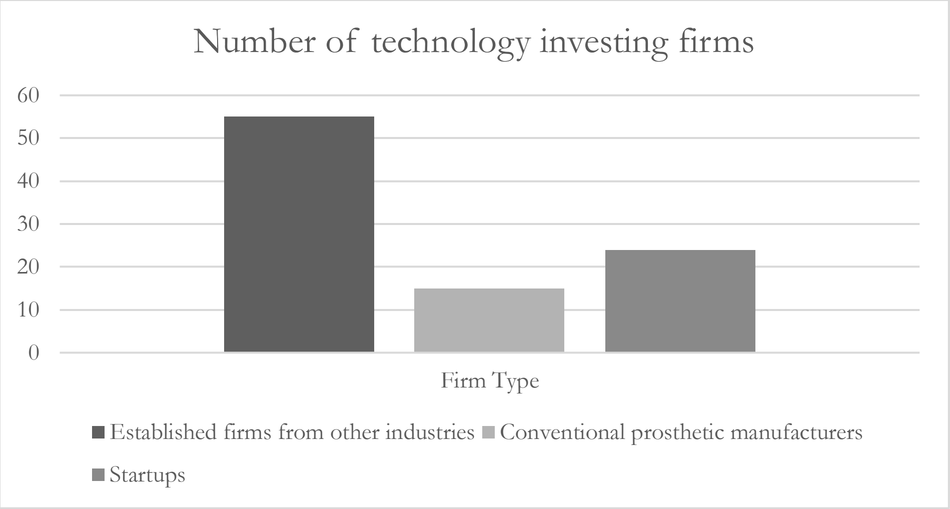


**Figure 5b: The number of firms investing in bionic technology, by firm type**

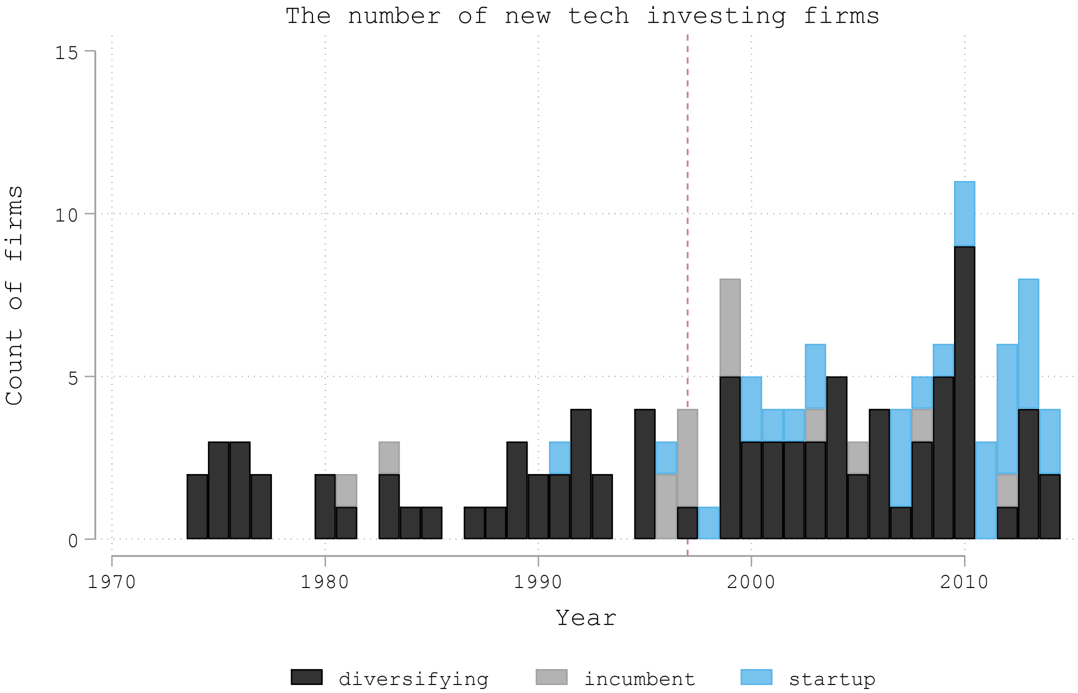


**Figure 6a: K-M survival analysis; Eventual outcome: exit by acquisition**

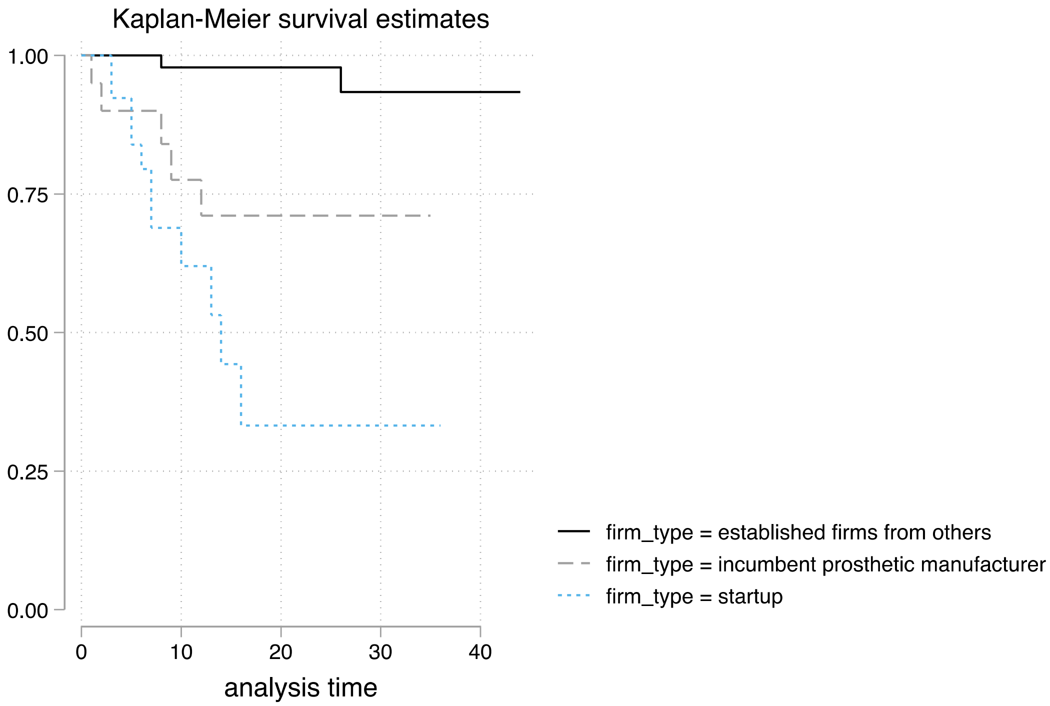


**Figure 6b: K-M survival analysis; Eventual outcome: entry to bionic limbs**

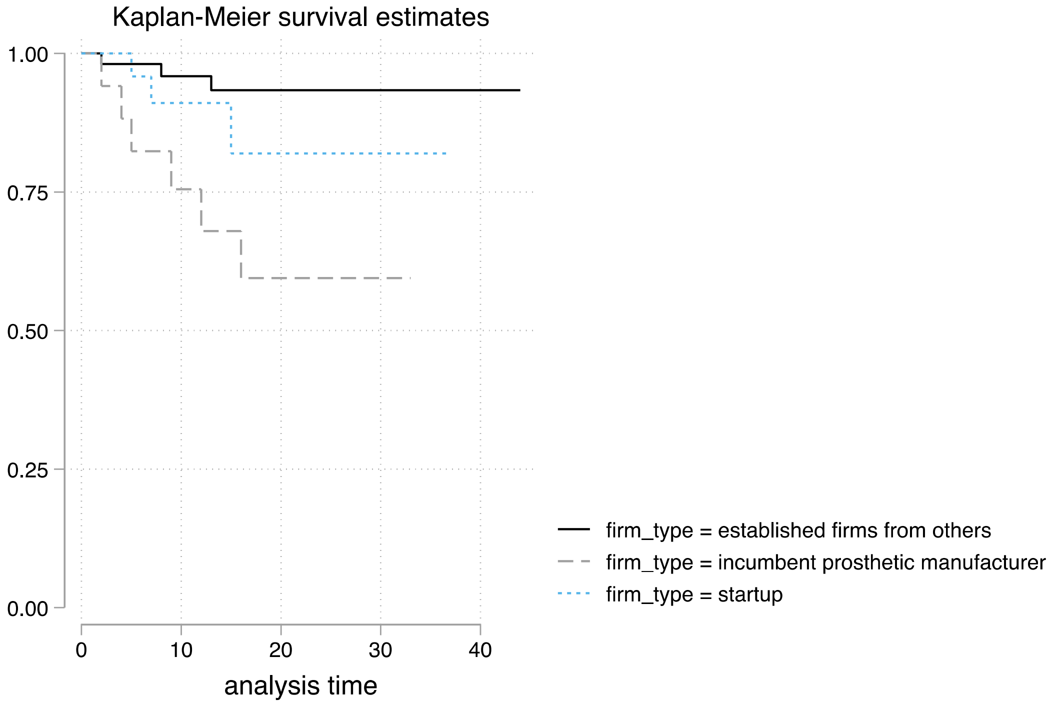
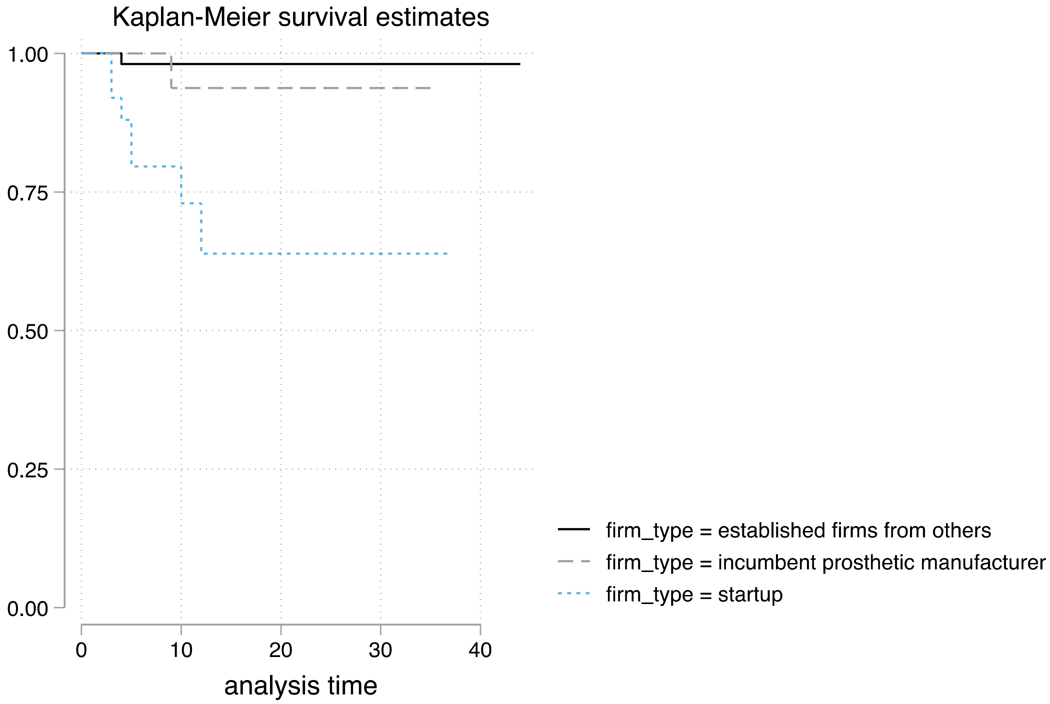


**Figure 6c: K-M survival analysis; Outcome: licensing during the study period**



(Note: Cross-sectional data. Technology entry years vary by firm. Right censoring occurs in 2018)

**Figure 7: Differing paths in knowledge development and value capture**

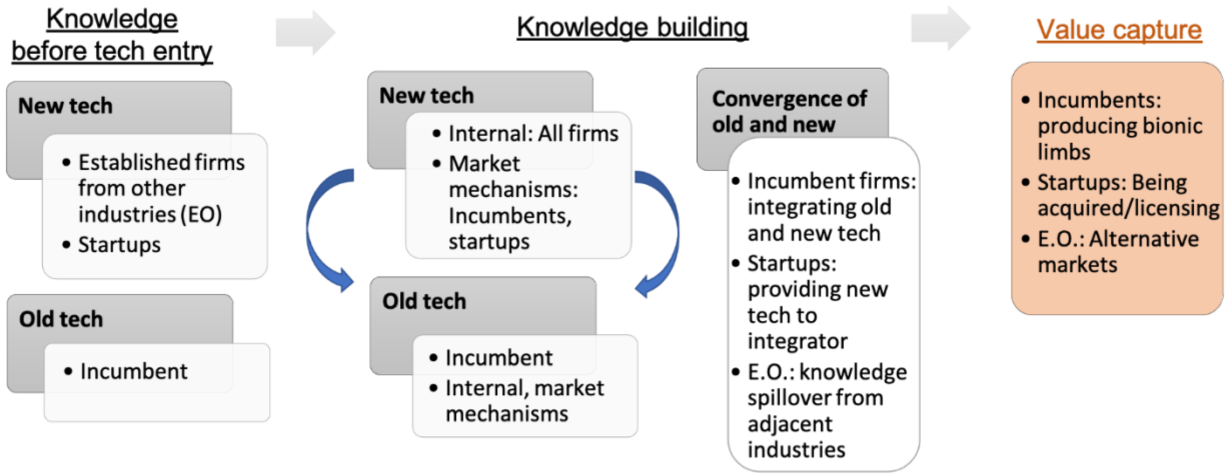


**Table 1: Comparison between the conventional prosthetics and the bionic prosthetics**

| Product Type | Market Inception | Sub-technologies within the system |
|---|---|---|
| Conventional Prosthetics | Around the World War I | • Materials: Steel, Aluminum, Titanium, Plastics, polycarbonates, resins, laminates, Carbon fiber, silicone, material processing<br>• Controls: Mechanical controls<br>• Design: Appearance, Mechanical designs, Fitting |
| Bionic Prosthetics | In 1997 | • Materials: Carbon fiber, Fiber-glass, Advanced plastic, Silicone<br>• Control: Microprocessors, Sensors (mimicking neural signals), Motors, Battery (mimicking human muscles), TMR<br>• Design: Appearance, Mechanical design, Fitting |

**Table 2: Constructs and data sources**

| Constructs | | Description | Data sources |
|---|---|---|---|
| Firm type | Incumbent prosthetic manufacturer | 1 if producing any prosthetic limbs by year t | Prosthetic firms' organizational and market history<br>• FDA Medical Device Register and Listing Database<br>• Medical Device Register and Listings annually released by Grey House Publishing (1984-2013)<br>• Corporate websites |
| | Other established firms | 1 if established firms in other industries by year t | |
| | Startup | 1 if no business history in other industries by year t | |
| Technological entry | The firm's first technological investment in the form of either internal R&D or other market mechanisms.<br>• Technological entry by internal R&Ds: filing patents and clinical trials.<br>• Technological entry by market mechanisms: collaborative R&Ds, licensing, patent acquisition, and division-level/firm-level acquisitions | | Patenting:<br>• The PatentsView database; The Fung Institute Patent Data; PATSEER<br>Other internal R&Ds:<br>• The O&P Edge; O&P Almanac; ClinicalTrials.gov; Nexis Uni<br>Acquisition:<br>• The SDC; Corporate Websites; Trade magazines<br>Alliance:<br>• Nexis Uni; Trade magazines |
| Value capture events within the focal market | Market entry | 1 if the focal firm produces bionic limbs in year t | Product launch:<br>• Major trade magazines: O&P Almanac (the 1950s-2018) & the O&P edge (2001-2018)<br>Acquisition:<br>• The SDC; Corporate Websites; Trade magazines<br>Alliance:<br>• Nexis Uni; Trade magazines |
| | Acquisition | 1 if the focal firm or the prosthetic business of the firm was acquired in year t | |
| | Alliance | 1 if the focal firm makes profits by licensing its technology or sales of patents in year t | |

**Table 3: Firm actions on the integration of radical technological systems**

| | | Established firms from other industries | Conventional prosthetic manufacturers | Startups | Total |
|---|---|---|---|---|---|
| Firms at risk | Tech investing | 52 | 20 | 30 | 102 |
| Entering the bionic prosthetic limb market | All market entry (a) | 3 | 12 | 8 | 23 |
| | Acquired afterward (b) | 0 | 3 | 5 | 8 |
| | Market Entry Only (a-b) | 3 | 9 | 3 | 15 |
| Acquired | Acquired | 2 | 5 | 11 | 18 |
| Integrated - Licensing/Sales of patents | Initial Licensing/ Sales of patents | 1 | 1 | 8 | 10 |
| | Acquired afterward | 0 | 1(also entered the market) | 5 | 6 |
| Others exits | Other exits | N/A | 1 (divesture) | 1 | N/A |

**Table 4: Firm histories on capability building and outcomes**

| Firm Type: Main role(s) | Capabilities prior to technology entry | Capability acquisitions | | Value capture within bionic prosthetic |
|---|---|---|---|---|
| | | New bionic technology | Old prosthetic technology | |
| Incumbent (4): Integrating old and new technology | Old (4) | Licensing: 4<br>Acquisition: 2<br><br>Startups, incumbent firms, Univ. | No action: 0<br>Upstream: 4<br>Downstream: 2<br><br>Acquisition (2) & alliance (4) | Entry to Bionic limbs: 3 (avg. 5 product lines)<br>Entry to complementary :1<br>Licensing: 0<br>Acquired: 0 |
| Startups (5): Providing new technology to integrators; Transferring academic research | Old (1)<br>New (4) | Licensing: 4<br>Acquisition: 2<br><br>Startups, Univ. | No action: 1<br>Upstream: 1<br>Downstream: 2<br><br>Alliance only | Entry to bionic limbs: 0<br>Entry to complementary: 1<br>Acquired: 3<br>-after licensing: 1<br>-after entry to bionic: 1(1 product) |
| Established firms from other industries (4): Knowledge spillover from adjacent industries | Old (0)<br>New (4) (electrical controls, robots, electronics, sensors) | Licensing: 4<br>Acquisition: 0<br><br>Startups, Univ. | No action: 2<br>Upstream: 2<br>Downstream: 1<br><br>Alliance only | Entry to bionic limbs: 1 (1 product)<br>Licensing: 1<br>Acquired: 0 |