Studies of radical technologies often begin with the first instance of their commercialization, defining them as technological shocks ushered by entrants which render existing technological competencies of established firms obsolete (Arrow, 1962; Henderson, 1993; Tushman & Anderson, 1986). Two concerns arise from such a definition. One, this *economic-effects* definition of radical technology conflates "what a radical technology is" with "who introduces the radical technology," and results in entrants having a technological advantage over incumbents *by definition.* Accordingly, incumbents may only adapt and respond but play no role in creating a radical technology (Eggers & Park, 2018). Two, a focus on the pre-history of *firms* to examine incumbent-entrant dynamics *post commercialization* ignores the pre-history of *the technology* in terms of its incubation. While recent studies have begun to address the second concern by studying the incubation period (Moeen, Agarwal & Shah, 2020), they have examined contexts where entrants take center stage (Gao & McDonald, 2022; Aversa, Furnari & Jenkins, 2022) and displace incumbents (Moeen & Agarwal, 2017). Thus, they remain silent on the first definitional concern and continue contributing to the dominant view of radical technology as an exogenous technological shock to incumbents.

In this study, we frame a radical technology as a product of an endogenous process that coevolves with the capabilities of economic actors who invest in its creation. In doing so, we examine the incubation and post-commercialization takeoff stages of a radical technology and revisit incumbent-entrant dynamics by asking the following research questions: *How do prior histories of economic actors affect their investments in incubating radical technological systems for value creation? And, how do economic actors' prior histories and technological investments impact their subsequent value capture strategies?*

To answer these questions, we create a framework that builds on the *nature of technology* definition: a radical technology is a solution that exploits novel principles in a technological system that serves a specific purpose (Arthur, 2009; Baldwin & Clark, 2000; Rosenberg, 1963). This definition is agnostic to *who* contributes to the creation of the radical technology and thus avoids the conflation of what a radical technology is from its effects on incumbent firms. It also enables a focus on *how* a fully functioning radical technological system may emerge through the recombination process of assembling novel components with necessary reconfiguration of existing components (Xiao, Mahkija & Karim, 2022). Such a framework has an immediate implication for understanding the strategic choices of economic actors: it is necessary to first identify who invested in incubating a radical technology, and why and how they did so. Only then can we examine post-commercialization dynamics, and how these investments enable economic actors to occupy complementary or substitute spaces in the emergent industry for value capture.

We illustrate our approach with an abductive study of the bionic prosthetic limb industry between 1974-2018. Prosthetic limbs are medical devices fitted to amputees to restore lost functions of natural limbs (US FDA, 2020). Prior to the first commercialization of a bionic prosthetic in 1997 and even to date, the dominant technological solutions utilize 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 novel base principles (electronics, robotics, neuroscience, and artificial intelligence) to create electrically powered control systems, interfaces that provide sensory feedback, and self-learning and adaptation of the prosthetics for greater functionality and ease of use.

We compile and leverage comprehensive quantitative data on the census of technological entrants in bionic prosthetics and deep historical narratives of five leading technological entrants in each firm type: incumbents in mechanical prosthetics, established firms in related industries, and startups. We uncover how and why the three firm types built on their prior knowledge to make important, often complementary, technological investments for the creation of component and system-level bionic prosthetic technology.

In terms of value creation strategies*,* all three firm types developed bionics and integrated them with other component technologies to create prototypes that amputees could use. However, the activities of different firm types varied. Incumbents' R&D efforts reflected simultaneous "upstream research" across more components, and more "downstream development" of prototypes for designing coherent and functional prostheses. "Small world" collaborative networks were created that included all three firm types, and path dependencies in technological investments emerged as technologies were sourced and co-developed through licensing and alliances.

In contrast, there is greater distinctiveness in the value capture strategies across the three types of technological entrants. Startups—largely founded by academics or user inventors—entered bionics component markets, engaged in alliances, or became acquisition targets. Incumbents combined their above-mentioned "technological system integration" efforts with downstream capabilities to dominate product commercialization entry in the nascent bionic prosthetics industry. Established firms from other industries were least likely to profit from their bionic prostheses technological investments through market entry, and few licensed their technology. Rather, while startups and incumbents built on their technology within the bionic prosthetics industry, established firms in other industries sought applications in other sectors, such as GM and Hyundai's mobility assistance of automobile factory workers and Honda, Parker, and Samsung's gait rehabilitation exoskeleton (Bloomberg, 2020; Honda, 2008, Parker, 2018, Samsung, 2020).

Our study contributes to existing work on industry evolution and incumbent-entrant dynamics (Eggers & Park, 2018; Tushman & Anderson, 1986) by providing a framework to evaluate how radical technologies might affect strategic positions of firms in an industry. Also, our work extends the budding literature on industry incubation by severing the "economic effects" definitional correspondence between radical technologies and incumbent technological obsolescence. We highlight the endogenous processes of radical technology creation and realized value capture strategies of *all* firms who invested in its creation (Moeen et al., 2020), not just established firms in related industries or startups (Cattani, 2005; Gao & McDonald, 2022; Moeen & Agarwal, 2017; Sanderson & Simons, 2014). Our framework also addresses selection bias in the literature at both industry and firm levels. At the industry level, we address the disproportionate sampling of industries where entrants usher radical technologies (c.f. review in Eggers & Park, 2018) to highlight nascent industry settings triggered by radical technologies where the forces of creative destruction on incumbents may be relatively weak. At the firm level, we address the selection bias in studies of incumbent-entrant dynamics sampling on firms who entered through commercialization (Bayus & Agarwal, 2007; Klepper & Simons, 2000; Sosa, 2013), thus missing firms who may capture value through alternative modes, including alliances (Moeen, 2017; Polidoro & Yang, 2021) and exaptation (e.g., Eggers, 2014, Garud et al., 2016). In doing so, we shed light on how and why established firms in other industries who make technological investments may not necessarily become "diversifying entrants." Here, our framework enables a stronger connection between industry evolution and corporate innovation literature (Katila & Ahuja, 2002; Xiao et al., 2022) for a better understanding of how entrants and incumbents may collaborate, not just compete, in radical technology and nascent industry settings (Moeen, 2017; Polidoro & Yang, 2021).

Finally, our "foundations of technology" approach complements the "profiting from innovation" framework, which has focused on complementary assets and intellectual property regime for value capture (Teece, 1986; Gans & Stern, 2000), and the "entrepreneurial strategy" framework which has examined entrepreneurial choice sets (Gans, Stern & Wu, 2019). We provide a framework to understand how the context limits the predictions of these theories. In particular, we highlight how prior knowledge and the systemic structure of technological solutions—the manner in which firm competencies fit for value creation—constrain and influence firm strategic choices independent of the presence of complementary assets (Teece, 1986; Gans & Stern, 2000) or possible entrepreneurial strategies (Gans, Stern & Wu, 2019).

CONCEPTUAL BACKDROP

"Economic-Effects" Definition of Radical Technology and Incumbent-Entrant Dynamics

In seminal work, Arrow (1962) defined radical (drastic) innovations as an advance that renders the old technology no longer a viable substitute. He further noted incumbents (particularly with market power) using the old technology to provide goods and services lack incentives to undertake optimal investments in radical innovation (also see Reinganum, 1983; Dew, Goldfarb & Sarasvathy, 2006). Similarly, Tushman and Anderson (1986: 441) used economic effects to define radical technologies as major discontinuities that offer "sharp price-performance improvements over existing technologies." They further distinguished between "competence-enhancing or competence destroying" radical technologies based on the effect on incumbent capabilities, noting "both technological discontinuities and dominant designs are only known in retrospect—technological superiority is no guarantee of success" (p. 443).

By correspondence, radical innovations that destroy incumbent competencies are more likely to be introduced by entrants (Gort & Klepper, 1982; Henderson, 1993), be they startups (Henderson, 1993), or diversifying entrants (Benner & Tripsas, 2012; Klepper & Simons, 2000; Sosa, 2013). Eggers and Park's (2018) comprehensive review underscores incumbents confronting radical technologies are either doomed, or they face the imperative to adapt. The incumbent-entrant dynamics literature is accordingly 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 focus on factors other than technological capabilities. Chief among these are complementary capabilities (Helfat & Lieberman 2002, Mitchell 1989, Tripsas 1997), (dynamic) capabilities for acquisition or assimilation of new technological knowledge (Cattani, 2005; Eggers, 2012), and cognitive attention, including willingness to cannibalize existing product lines (Benner & Tushman, 2002; Chandy & Tellis, 1998; Eggers & Kaplan, 2009; Tripsas & Gavetti, 2000).

The empirical implication of the economic effects definition is that almost all studies sample on industry contexts where entrants ushered the radical technological change (Bayus & Agarwal, 2007; Klepper & Simons, 2000; Mitchell, 1989). Moreover, the overwhelming majority of studies of incumbent-entrant dynamics begin at the first instance of product commercialization, and sample firms based on *product market* entry. Recent work has illuminated that technologies are incubated well prior to this milestone (Moeen & Agarwal, 2017) through technological investments by numerous and heterogenous actors (Cattani, 2005; Malerba & Orsenigo, 1999), and vibrant activity in markets for technology and corporate control (Moeen & Mitchell, 2020). Though, even these studies sampled on contexts where entrants take center stage, whether they be diversifying entrants (Moeen & Agarwal, 2017), or startups (Gao & McDonald, 2022).

"Novel Base Principles" Definition of Radical Technology

Henderson and Clark (1990) conceptualize technology as consisting of core design concepts embodied in components linked together in an architecture and define radical innovation as the use of new design concepts and architecture. Furthermore, Baldwin and Clark (2000) define technology as a complex system consisting of interdependent and hierarchical components and suggest that a key to designing technology is managing tradeoffs and optimizing functions within and across design parameters of components. Arthur (2007) further crystallizes a technology *as a system designed to serve a purpose*. He notes "a technology ... possesses a purpose, a combination of components, an architecture, and embodies a base principle that exploits some base phenomenon" (p.277) and defines a radical technology as one that "achieves a purpose by using a new or different base principle than used before" (p. 278).[2] [3]

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[2] 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"

[3] To illustrate definitional comparisons, Eggers and Park (2018) classify biotechnology, generational shifts in disk drives, and digital photography as radical technologies based on economic effects. However, only biotechnology and digital

The interplay between a technology's purpose (problems it solves) and the use of new principles for developing radical technologies harks back to Rosenberg (1963; 1974), who additionally examined the pursuit of new scientific discoveries to breakthrough constraints of available technological and scientific knowledge. Such breakthroughs often serve as a basis for several new technologies, where each new technology applies a novel principle to achieve a specific, intended purpose. Thus, new base principles can spawn several new industries as different actors develop various radical technological solutions that enable the useful application of the new base principle to different human needs, or problems.

Moreover, within a technological system, components themselves represent "subtechnologies" (Arthur, 2009). For example, the introduction of the jet engine was a radical subtechnology in broader airplane technology, because it used different base principles than internal combustion engines. Creating a complete solution requires a deliberate process wherein the radical subtechnology is integrated with other subtechnologies, which themselves may need to be refined or reconfigured. Thus, the creation of radical technologies requires attention to what Rosenberg (1969) stated is a "sequence—changes in one component of an interdependent system creates a stimulus for changes elsewhere in this system" (p.9). Regardless of where a novel base principle is used, a core aspect of the process is that new base principles require reconfiguration of components into a new architecture. As noted by Arthur (2007), "translating [a] base principle into physical reality requires the creation of suitable working parts and supporting technologies," some of which "may require inventions of their own" (p. 278). Thus, a radical innovation entails "matching a need to a principle (or effect envisaged in use) and solving the ensuing hierarchy of problems and subproblems. Thus, radical technologies require waves of economic experimentation wherein both failed and successful efforts generate valuable information regarding trade-offs encountered in both the recombination of scientific principles and their economic implementation (Rosenberg, 1992).[4]

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photography are radical per the nature of technology: biotechnology uses biological techniques to develop therapeutic drugs, and digital photography stores image information digitally as opposed to chemically. That is, the base principles are new. The shift across disk drive generations is not radical, because storage continued to employ magnetic principles.

[4] Such a process is illustrated in Rosenberg's (1963) exposition of the development of the nascent machine tool industry. More recently, Pillai, Goldfarb, & Kirsch (2020) note the "automobile" technology—use of engines to serve the human need for road transportation—relied on the integration of a) a radical solution for propulsion (the internal combustion engine), b) many new technologies developed to better complement the capabilities of the new propulsion technology (e.g. the use of rubbers and tires), and c) many known technologies of horse-carriages that were either unchanged or incrementally improved (e.g. use of wheel).

While explicitly recognizing that radical technological systems require an iterative process of experimentation, this literature is nonetheless silent on the role of economic actors, particularly in defining *who* partakes in the process and *why*. In part, this is because the level of analysis typically employed in technology studies is either at the technology or at the "economic system" level. For example, Rosenberg (1979) and Arthur (2009) note 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. However, they are both relatively silent on the strategic considerations of the economic actors and their impact on how and whether new capabilities are introduced, and old ones reconfigured by new or existing organizations.

CONCEPTUAL FRAMEWORK

Our conceptual framework integrates the "novel base principles" definition of a radical technological system with the strategies undertaken by heterogeneous economic actors for its creation and subsequent value capture. In doing so, our process model answers the following questions: *How do prior histories of economic actors affect their investments in incubating radical technological systems for value creation? And, how do economic actors' prior histories and technological investments impact their subsequent value capture strategies?*

A Process Model Linking Prior Histories to Creation of Radical Technologies and Competencies for Subsequent Value Capture

We base our framework on the premise that in order to understand how a radical technology may shape firm strategy and industrial organization, one must begin by describing the nature of the technology and then pinpoint the role of economic actors who invested in incubating a radical technology and why and how they did so. Novel base principles are, by definition, different from past ways of doing things, and human needs are defined, in part, by social structures, organizations, and existing technologies. Thus, there cannot be a general rule, even theoretically, as to how a radical technology will impact existing market players (Goldfarb & Kirsch, 2021). Instead, the development of a radical technological system is endogenous to, and will coevolve with, the capability investment of heterogeneous actors. Figure 1 provides the conceptual map of this co-evolutionary process and guides our empirical efforts in the next section.

[Figure 1 about here]

Heterogeneity in Prior History and Knowledge of Economic Actors

Recent work on industry incubation (c.f. review in Moeen et al., 2020) notes that within the cumulative knowledge building process, a particular technology's incubation period is often triggered by inventions that employ new base principles or scientific discoveries to envision a solution for practical use. Such triggers garner attention from a diverse set of economic actors who possess relevant knowledge and are driven by their aspirations for creating the radical technology. Our use of the term "economic actors" at this stage is intentional[5]: beyond established firms in focal or related industries, the term encompasses academic, public and nonprofit organizations (Agarwal, Kim & Moeen, 2021; Roy, Lampert & Sarkar, 2019) and individuals aspiring to build the radical technological system based on insights gained through invention or user unmet needs(Agarwal & Shah, 2014; Franke & Shah, 2003; Mowery & Rosenberg, 1991; Shah, 2003; Sanderson & Simons, 2014). In addition to the diversity in form, the economic actors also represent heterogeneity in their prior history and knowledge context. In particular, these knowledge contexts embody experiences making scientific discoveries and inventions related to new base principles, serving or using existing technologies for focal purpose (embodying existing base principles), or serving a different purpose using sub-components relevant for the focal purpose.

Creation of A Radical Technological System And Competencies

The incubation period itself is characterized by a recursive process of investments, experimentation for trial and error, and knowledge sharing through appending and aggregating mechanisms (Moeen et al., 2020). Such a process helps build the knowledge base for creating a new technological system through focused cognitive attention for identification or creation of 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 by their prior history, which influences both their aspirations and abilities to create component or architectural knowledge creation and access the complementary knowledge created by others. For example, inventors who seek to leverage new scientific principles in focal purpose applications may focus on creating novel component or system prototypes (Kim, 2021). Moreover, established firms may draw inspiration and rely on their existing routines and processes

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[5] We include "economic" in the term because regardless of who the actors are, their investments are nontrivial in terms of human effort and opportunity cost of alternative use of resources and capabilities.

when creating components or reconfiguring architectures (Girod & Karim, 2017). These pathways are nonlinear. They include parallel play and potentially competing investments by individual or group of economic actors (McDonald & Eisenhardt, 2020), non-market collaboration within small clusters (Aversa et al., 2022; Franke & Shah, 2003; Mody, 2006), and formal market-based alliances and acquisitions (Moeen & Mitchell, 2020) to create, combine, and reconfigure component and architectural knowledge. Such pathways also have implications for emergent and reconfigured organizational forms: individuals may leave existing organizations (e.g., academic institutions or established firms) or leverage user innovation to create new ventures (Agarwal & Shah, 2014), and corporations may reconfigure business units through spinoffs or acquisitions for changes in firm boundaries (Karim, 2009; Moeen & Agarwal, 2017; Sanderson & Simons, 2014). Together, such incubation period investments, and associated formation/reconfiguration of organizations through collaboration and competition not only develop a radical technology, but also position firms (startups, incumbents, and established firms in related industries) to leverage their investments in an emergent industry, post the commercialization milestone (Moeen et al., 2020).

Economic Effects and Value Capture Strategies

Given vibrant technological investments, formal and informal collaborations and (re-)configuring of firm boundaries that occur during industry incubation, the first instance of product commercialization is certainly an important milestone, but perhaps not as much a watershed event as has been accorded in prior studies (e.g. Gort & Klepper, 1982; Tushman & Anderson, 1986). The pioneering firm who commercializes the first functional product utilizing the radical technological system may simply be the first among many firms who had begun their journey well before this milestone. Importantly, the prior history and radical technological system creation strategies for generating component and system level technological knowledge also have implications for value capture strategies in the emerging industry that utilizes the radical innovation. Commercialization is only one of three potential value capture strategies. Commercializing firms—formally termed *product market* entrants—need to complement the radical technological system capabilities created through the prior stages with other capabilities (e.g. operations, downstream marketing and distribution) to profit from innovation (Teece, 1986; Mitchell, 1989; Tripsas, 1997). The extent to which these value chain activities access relevant capabilities already possessed by established firms (incumbents in focal industries or established firms in related industries) will determine their commercialization advantage over startups (Teece, 1986). Alternatively, firms who invested in creating components or entire technological systems may choose to sell their technological capabilities in markets for technology—formally termed *alliance partners* in upstream markets. Such alliances may represent ongoing collaborations from the prior stage, as when established firms (in focal or related industries) or startups engage in technological alliances with each other (Bikard & Marx, 2020; Kapoor & Klueter, 2015; Mitchell & Singh, 1992; Rothaermel & Boeker, 2008) or corporate investment relationships (Polidoro & Yang, 2021). Finally, firms may also undertake active reconfiguration of capabilities and business units in anticipation and post commercialization of the radical technological systems—formally termed *acquirers* or *acquirees* in markets for corporate control. The acquirers are likely to be product market entrants, and acquirees could include startups, incumbents or established firms in related industries who either choose to be wholly acquired or divest relevant business units (Karim, 2009; Moeen & Agarwal, 2017).

Reconciling the Process Model with Economic Effects and Incumbent-Entrant Dynamics

Our process model utilizes the "novel base principles" definition of radical technological systems (Arthur, 2009; Henderson & Clark, 1990) and overlays a knowledge creation and recombination perspective on the incubation and emergence of nascent industries (Moeen et al., 2020, Xiao et al., 2021). Doing so enables us to address several theoretical issues with the literature based on economic effects and resultant incumbent-entrant dynamics. Concomitantly, the framework also opens up opportunities to address empirical selection biases in the industry evolution literature at both technology and firm levels.

First, the novel base principles definition avoids the circularity of radical innovation based on a "market test" in terms of its effects on incumbent technologies. Defining a radical innovation based on its *nature*—the use of novel base principles—allows for a separation between attributes of a technology and which organizations possess relevant technological capabilities. Discovery of new base principles and pursuit of their applications may be conducted in academic or corporate research labs (Nelson, 1959; Mowery & Rosenberg, 1999), enabling inventors to form startups or established firms (in focal or related industries) to possess and develop relevant technological capabilities. Use of new base principles does not *have to* map onto organizational capabilities of entrants, even though it *may*.[6]

Second, a technological system view wherein a new working architecture consisting of new and reconfigured components 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 (Arthur, 2009; Xiao et al., 2022). New component and architectural knowledge will be radical, but the change will not always make *all* old technological capabilities obsolete. Which capabilities retain value is a function of the underlying base principles *and* endogenous design choices in system incubation wherein diverse economic actors make investments: these include individuals embedded in relevant knowledge contexts (Agarwal & Shah, 2014), and organizations in focal and related industries. The use of new base principles *need not* create obsolescence and substitution of component knowledge, even though it *may*.

Taken together, the above two conceptual attributes remove the need to create additional economic-effects based classifications of radical technologies as competence destroying or competence enhancing. 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

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[6] Of note here are the COVID vaccines developed using mRNA technologies vs. conventional methods relying on vaccines that inject antigens (a piece of the virus) into the body (Loftus, Hopkins & Panceviski, 2020). 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.

[7] Interestingly, archival reports (IBM archives, n.d.) 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 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 underscores that the competencies were not developed inhouse by incumbents, but acquired through alliances or acquisitions.

base principles permits classification of the technology as radical because of the shift from mechanical to electrical principles, and concomitant changes in components and architectural redesign.

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 to accomplish a task—accommodates industry contexts where radical and existing technologies may co-exist because they cater to different purposes with distinct price-performance parameters. In such cases, radical technologies can lead to periods of experimentation where incumbents and entrants engage in capability investment and product entry, with neither the need nor the fear of cannibalization. For example, in the medical diagnostic industry, entrants and incumbents alike invested in technologies that relied on different base principles: X-ray, magnetic resonance, nuclear medicine. These technologies cater to different needs (e.g., bones vs. tissue and organ scans) and offer different price/performance tradeoffs. Moreover, it also opens up the examination of industries born from technology convergence or general-purpose technologies with applications across different industries (Rosenberg, 1979). For example, digitization as a general-purpose technology created a change of chemical principles 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 (the Internet), and cable television industries. Making radical technologies useful often requires the creation of new technological systems, though the component, subtechnologies 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*. Also, technologies and/or the organizations who apply them *need not* be in direct competition with each other, even though they *may*. Together, these conceptual attributes relax the need for sampling on industries and technologies based on whether the radical technological system was ushered by entrants, additionally creating the notion of a "dominance by birthright" of diversifying entrants (Klepper & Simons, 2000). It allows for the systematic study of industry evolution in contexts where incumbents play a critical role in creating a radical technological system, in conjunction with other economic actors.

Fourth, by fully integrating firm prehistories with technological investments during the incubation period, the framework avoids the conceptual and empirical selection bias in existing industry evolution studies regarding relevant economic actors, their interactions, and their organizational transformations. A conceptual and empirical focus on post-commercialization stages of the industry (Gort & Klepper, 1982; Tushman & Anderson, 1986) masks who invested in incubating the industry in the first place, and additionally privileges only those firms who enter markets for commercialization. The formal incorporation of the incubation period allows for a systematic study of heterogeneous builders of the system, beyond commercial entrants. Importantly, modes of value capture (commercialization, alliances, acquisitions) are not random, but endogenous to prehistories and technological investments in the incubation period (Moeen & Agarwal, 2017). Extending to the incubation period and incorporating multiple modes of value capture relaxes the assumption that entrants and incumbents are always competing with each other and accommodates collaboration in incumbent-entrant dynamics for a vibrant ecosystem that creates and aggregates knowledge to develop a technological system (Moeen & Mitchell, 2020; Polidoro & Yang, 2021).

We next turn to an empirical illustration of our framework in the bionic prosthetics industry with the near census of technological entrants from the incubation of the bionic technology to post-commercialization. In the following, we describe our research context, the emergence of the technological system for bionic prosthetics.

RESEARCH CONTEXT: BIONIC PROSTHETICS

The first known experimentation on bionic prosthesis was by physicist Reinhold Reiter in the early 1940s (Childress, 1985). Technological investment in bionic limbs grew in the late 1960s and through the 1970s, spearheaded by university labs (e.g., MIT, Johns Hopkins Applied Physics Lab) and firms such as Otto Bock orthopedics and Liberty Mutual (Childress, 1985). The first fully microprocessor-controlled bionic limb—Otto Bock's C-leg—was introduced in 1997 in Germany and received FDA approval for commercialization in the U.S. in 1999 (U.S. FDA, 1999).

Bionic prostheses serve the purpose of providing amputees with lost functions of natural limbs. Relative to mechanically controlled prosthetics, bionic prosthetics offer users much greater degrees of freedom in their limb movements, enabling diverse activities ranging from climbing hills and running on uneven surfaces to natural and delicate motions such as gripping and pinching. [8]

Both mechanical and bionic prosthetics represent a technological system that utilizes three critical sub-technologies: materials, controls, and design. Table 1 displays key similarities and differences between the two systems.[9] The most distinctive feature across the two systems is within the *controls* sub-technology. Mechanical prosthetics use body-powered energy created within a movement cycle, utilizing hinges made of locks and brakes to stabilize movement and hydraulic or pneumatic mechanisms to control speed and energy. Bionic prosthetics shift sole focus on mechanical base principles to include bionic base principles that combined electrical engineering, robotics, and neuroscience (Burck et al., 2011; Ravitz et al., 2013). The use of bionic base principles enable new technical features: these include an interactive interface between the prosthesis and the residual limb for intuitive controls and sensory feedback, and artificial intelligence (AI) based technology that allows a device to adapt to the user with use.

Rather than a mere modular change, the new control subtechnology involves substantial changes in materials and requires a redesign of the device structure and a new fitting mechanism based on new base principles. Within materials and design, there are several similarities but also stark differences due to the need for integration across sub-technologies. Within materials, desirable properties such as lightweight, durability, and energy-restoring were achieved in mechanical prosthetics using metals (e.g., iron, aluminum, titanium) and composites (e.g., rubber, plastic, silicone, carbon fiber) (Conn, 2012). Bionic prosthetics favor the subset of lighter and more weight-bearing composites (e.g. carbon fiber, advanced plastics) to accommodate the weight of artificially powered mechanisms. Moreover, the need for creating sensation and neural interfaces requires the use of novel materials such as tactile skins, biocompatible and implantable materials, and electromagnetic composites. In design, similarities arise from the need for fit (e.g., sockets and liners) and for

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[8] Prosthetic limbs satisfy the end user's need for mobility. These needs include (1) function, e.g., durability and improved mobility with greater controls over the device; (2) fitting—e.g. be wearable, less cumbersome and stiff; and (3) appearance—e.g. look like a part of the natural human body, pleasing aesthetics. Bionic prosthetics improved functionality and inevitably involved significant changes on fitting and appearance.

[9] Although prosthetics date back to at least the 16th century, modern-day mechanical prosthetics (starting from WWI) represent continuous advancements in material technology—from wood and leather to more advanced materials noted in Table 1. Similarly, within design, critical advancements included modularization for increased interchangeability of parts and mechanical controls (e.g., tubes, pylons, valves) in the 1970s (Staros, 1979), as well as C-shaped running blades conceptualized in the 1980s and popularized onward (Pogash, 2008). See Appendix Figure B1.

appealing aesthetics (e.g., lifelike covering and shade options).[10] Here, prescriptions of prosthetic devices are based on the evaluation of patients' physical and mental conditions and need for mobility (Davis, Kelly, & Spires, 2013). Differences stem from design optimization to match features and benefits enabled by the shift from mechanical to bionic controls. For instance, mechanical prosthetics customize limb shapes for specific activities (e.g., C-shaped blades for running, fin-shaped feet for swimming, hook-shaped hands for daily activities, and wrench-shaped hands for heavy-duty work). Instead, bionic prostheses often use complex designs replicating human anatomy for diverse motions (e.g., hands with individually actuated five digits). Bionic controls also often utilize new principles for fitting. Osseointegration (i.e., implanting synthetic connectors) provides more secure connection, but also sensory feedback, so bionic prosthetics sockets are not mere connectors but must also record electric signals from the body (Moran, 2011; Umbrell, 2019).

[Table 1 about here]

Bionic prosthetics is a fruitful context in which to examine our question. As noted above, bionic prosthetics conform to the radical technology definition of the use of *novel base principles* to create a new technological *system* composed of various sub-technologies. This context also enables us to link a radical technology to industry emergence in terms of the key economic actors, their capability development processes, and their subsequent value capture strategies. Such a linkage between technology and industry emergence is affirmed in historical archives that note bionic prosthetics to be one of the most significant technological advancements in prosthetic history and led to the surge of new products in the orthopedics and prosthetics (O&P) industry (Fairley, 2014).[11]

DATA AND METHODS

We track the emergence of bionic prostheses throughout industry's incubation (1974-1996) and post-commercialization (1997-2018). 1974 marks the year when the first bionic prosthetic patent filed by a firm is recorded in our data. Triangulation of data sources enabled us to identify the relevant actors who collectively

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[10] Fitting refers to the connecting of the device to a patient's body with a socket, suspension system or fitting components. Fitting involves measurement, casting, device alignment, optional cosmetic coverings and follow-ups.

[11] For example, Össur, a prosthetic manufacturer noted in their annual report that the rapid technological innovation and new product developments resulted in 50% of its revenues during 1999-2001 stemming from new products, in comparison to a 20% in 1997 (Össur's Annual Report, 2001).

drove technological and industry emergence, and to acquire a broad understanding of the sequence of their actions and outcomes (Forbes & Kirsch, 2011; Santos & Eisenhardt, 2009; Wadhwani & Jones, 2014).

We use an abductive method (Heckman & Singer, 2017; King, Goldfarb, & Simcoe, 2021) to infer the best explanation by analyzing both quantitative data and business case studies over the industry's history. Quantitative analysis of a comprehensive census of all technology investing firms allows us to understand the technological trends in the nascent bionic prosthetic device industry. These analyses also provide associative relationships to infer plausible explanations (Agarwal, Braguinsky & Ohyama, 2020). We complement this with a deeper dive into historically significant business cases of 15 firms that made substantial technological investments in bionic prosthetics, stratified by their prior experiences. The business histories enable us to understand the evolution of firm capabilities, creation of the radical technological system, and value capture strategies through path-dependencies in the building of firm capabilities and allows for an informed interpretation of firm actions (Forbes & Kirsch, 2011; Lippmann & Aldrich, 2014; Wadhwani & Jones, 2014).

QUANTITATIVE ANALYSIS

Data Sources

Table 2 lists the sources utilized for compiling a comprehensive database of firms that made technology investments in bionic prosthetics ("technological entrants") through internal (i.e., patent applications and clinical trials) and external (i.e., acquisitions and alliances) R&D efforts and their value capture strategies. For internal R&D, we primarily used the PatentsView database to identify patents with immediate applications to bionic prosthetic limbs and also identify firm assignees of bionic limb prosthetic patents. Medical devices represent an industry where technological investments are heavily patented (Chatterji, 2009; Hall, Jaffe, & Trajtenberg, 2001; Smith & Shah, 2013), and prosthetic devices have high patenting rates beginning in the late 19th century (Clemens & Rogers, 2020). Our reliance on patent applications as a key measure of internal R&D investments is consistent with studies of technology evolution (Cattani, 2005; Malerba & Orsenigo, 1999). Also, we identified additional technological entrants by tracking firms' clinical trials and R&D effort related to bionic prosthetics using the U.S. registry of clinical trials (www.ClinicalTrials.gov) and media mentions in industry news.

[Table 2 about here]

Specifically, using the United States Patent Classification (USPC), we identified patents classified in prosthetic limb-related technological classes (Table A2-(a)) such as prosthetic leg, arm, components, actuators, and connectors. Within these patents, bionic prosthetic patents are those that are also assigned to technological classifications associated with critical features of bionic prosthetic limbs based on their inclusion in any of the technological classes in Table A2-(b), such as bioelectric controls, human-machine interface, computer & communication and electric and electronic classes. We validated the relevance of the classes by investigating core patents listed in industry reports, patents of firms mentioned in media as bionic prosthetics innovators, and by consulting with two patenting analytic firms, Innovaccer and Patseer. Several additional steps ensured our corpus of patent applications captures firms' technological investment in bionic prosthetic limbs accurately and comprehensively. We repeated the above procedure with the Cooperative Patent Classification (CPC) on the entire population of US patent in the sample period (Table A2). This ensured a) the change in the U.S. patent office's technological classification system in 2015 did not cause us to miss any relevant, innovative activity, and b) our sample covers more recent firms patenting activities after the year 2015. We also verified search results with alternative algorithms relying on technology classifications and the textual information of patents (see Table A1 in Appendix for more detail) and identified pending patent applications that may not be included in the PatentsView. To further ensure the mapping of patents onto bionic prosthetics, the final set of patents used for analysis were restricted to those subsequently cited by at least one granted patent in the prosthetic limb technological subclasses (Table A2-(a)).[12]

To capture firms entering through external R&D investments and measure value capture strategies noted below, we compiled data on acquisitions and technological alliances from the SDC Platinum database within two relevant SIC codes—3842 (Orthopedic, Prosthetic, and Surgical Appliances and supplies) and 3845 (Electromedical and Electrotherapeutic Apparatus). We also relied on industry news published in trade magazines, LexisNexis, and corporate websites and annual reports.

These efforts enabled us to identify the near census of 111 firms that made technology investments in bionic prosthetics during the 1974-2018 period, based on information on patent assignees, initiators of

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[12] This criterion is to exclude patents with little use for prosthetic applications. The unrestricted sample yields consistent results. Pending applications were manually investigated to ensure that citing firms included prosthetic firms.

clinical trials, and firms listed as engaging in alliances or acquisitions. Our data include 33 startups, 23 incumbent prosthetic manufacturers, and 55 established firms operating in other industries.

Variable Definitions

We tracked the first time a firm invested in bionic prosthetics in any form to mark its *technological entry* (Malerba et al., 1999; Cattani, 2005) and the intensity and nature of its technology investments through patents over subsequent years. The firm type, *startups, incumbent prosthetic firms, and established firms from other industries (other established firms),* is defined based on the firm's business history prior to its technological entry. Table 2 provides the operationalization of each firm type.

Bionic prosthetic technology systems include several subtechnological systems (bionic; mechanical control, design, and material). Table A2 lists technological classes corresponding to each of the four subsystems (Rows (b)-(e)). We index a patent in each of the four subsystems. Additionally, at the firm level, we define an indicator variable *Firm-level technological integration* set to one if the firm filed patents in bionic prosthetics technology classes and also possessed prosthetic patents belonging to the other three subtechnological systems, and zero otherwise. This allows us to capture if a firm investing in bionic prosthetic technology also had knowledge in the other subtechnological systems. Our second measure, *Count of Firm-level Technology Integration* takes the value of 1 through 4 to measure the number of subtechnological systems represented in a firm's patent portfolio. The minimum value is set to 1 (i.e., the firm possesses patents only in bionic subsystem), and the maximum value is 4 (i.e., the firm possesses patents across all four subsystems).

Finally, we compiled data on subsequent value capture strategies of all firms. Per Moeen & Agarwal (2017), we measure whether a firm a) commercialized a product through *Market entry,* additionally distinguishing entry into a bionic *component* or prosthetics *system*, b) *Provided technology in alliance* or c) was *Acquired* by other firms in the bionic prosthesis space. *Market entry* was measured by product launch events, ads in two major trade magazines and other press releases, and data on technological alliances and acquisitions were compiled from sources as listed above for tracking technological investments. Table 3 provides the firm-level descriptive statistics.

[Table 3 about here]

Analytical Methods

We chart industry-level trends in patenting and sales, key features of technological entrants such as firm type, technological investment patterns, and associated value capture strategies. We use linear probability (and ensure robustness to logit) models for associations between firm types and (a) capability development in components or system level integration and (b) value capture strategy. Specifically, at the firm-level, we estimate the following models:

$$\text{(a): } Technological\ integration_i = \beta \cdot X_i + \ \delta \cdot Firm\ Type_i + \varepsilon_i$$

$$\text{(b): } Value\ capture_i = \beta \cdot X_i + \ \delta \cdot Firm\ Type_i + \varepsilon_i$$

The capability development regressions examine whether firms are more likely to internally invest in components or system integration prior to their first value capture event. As noted above, we measure technological integration in two ways: the *Firm-level integration dummy*, and *the number of subtechnologies integrated.* The value capture regressions examine the firm's value capture strategy. As noted above, each value capture regression examines whether the firm engaged in *Market entry (system or component level), provided technology in an alliance,* or was *Acquired.*[13] In each regression, the coefficient δ captures the association with $Firm\ Type_i$, with incumbents as the baseline group. We control for the cumulative count of prosthetic patents in (a) and bionic prosthetic patents (X_i) in (b), respectively.

Since our analyses were not prespecified, we interpret the presented regressions as patterns that fit the data drawn from our census of bionic technology investing firms. We describe our results in terms of precision and consistency with explanations, smaller standard errors relative to a coefficient are interpreted as indicating a greater likelihood that a particular model is consistent with the data. That is, we do not interpret test statistics as informing the probability that a particular estimate is a result of chance, nor interpret our results as *tests* of our theoretical framework consistent with recent recommendations (King et al., 2021). Our use of an abductive approach implies that the findings informed the development of theoretical insights.[14]

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[13] Each of the value capture regressions examine whether firms ever used that value capture strategy during our observation period (irrespective of whether they also engaged in other strategies). Tables A5 and A6 presents consistent results based on the firm's first-time and final value capture strategy, respectively (i.e., using only the first or last value capture strategy for firms who utilized multiple value capture strategies during their observed history). About 25% of the firms (11 firms: 3 incumbents, 7 startups, and 1 other established firm) engaged in multiple value capture strategies as of 2018 (10 firms used two strategies and one firm used 3 strategies).

[14] In contrast, a deductive approach would have entailed a temporally distinct research process of theorizing and pre-specification of a sampling, measurement, and testing plan prior to engaging in any data collection.

Key Trends in Technology and Industry Emergence

Figure 2 depicts trends in bionic prosthetic patents and important technological milestones, starting from 1974, the first year in our bionic patent data. The patenting trend reveals minimal activity through the mid-1980s, and a sharp acceleration beginning in the late 1990s, spurred primarily by advances in information and computer technology. Figure 3 depicts (a) the cumulative number of firms who entered the prosthetic technology space throughout the observation period, (b) the cumulative number of firms who commercialized a bionic prosthetic product or component throughout years (c) market sales based on Medicare spending on bionic limb prostheses in each year.[15] In both technological and product market spaces, there is a monotonic increasing trend: cumulative technological entry accelerates earlier (starting in the mid-eighties) than market entry (starting in 1997), and is at a larger scale throughout the sample period. Moreover, Figure 3 depicts a sharp increase in sales starting in 2004. Taken together, Figures 1 and 2 showcase a deepening of technological activity within an increasing number of firms. These trends and associated incubation, firm and sales takeoff stages in bionic prosthetics are consistent in terms of both duration and patterns with those reported for other industries (Agarwal & Bayus, 2002; Golder, Shacham, & Mitra, 2009; Moeen & Agarwal, 2017).

[Figures 2 and 3 about here]

Capability Development and Creation of the Bionic Prosthetics Technological System

Heterogeneity in Economic Actors

We begin by describing firm heterogeneity in prior histories and technological entries. Among the 111 firms who invested in creating bionic prosthetic technology, 30% are startups, 20% are prosthetic incumbents, and 50% are other established firms (Table 3). This pattern of numerosity and diversity in technological entrants is consistent with findings in studies of fiber optics (Cattani, 2005) and agricultural

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[15] We use cumulative entry rather than number of active actors for a particular year because the latter requires information on exits, which we lack for the technological space. Nonetheless, cumulative entry captures what we want to examine, i.e., the numerosity and intensity of technological and commercialization efforts. Also, we note that data on sales are systematically available only from Medicare records. Medicare covers approximately 30% of the medical payments for prostheses and sets standards of reimbursement for private insurers. Thus, these sales trend correlate but underestimate revenues associated with bionic prosthetics. This is because the majority of prosthetic devices are paid for by public and private healthcare insurers, similar to other medical devices and healthcare services. Moreover, Medicare beneficiaries are people who are over 65 years old, so the underestimation is also due to omission of younger prosthetic users who tend to be much more active and more eligible for high-functioning devices. Nonetheless, Medicare spending is an important index for sales and growth trends, widely accepted by various participants in the O&P field.

biotechnology (Moeen & Agarwal, 2017). Moreover, 60% of the startups represent academic entrepreneurship, defined as new ventures founded by academic researchers whose ideas originate from their research expertise in bionic technology (Kim, 2021). Most incumbent firms (87%) did not have businesses outside the prosthetics and orthopedic industry, which was common in the conventional prosthetic industry. As the largest group of technological entrants, other established firms hailed from multiple industries including other medical sectors (38%), medical science and technology engineering (15%), and non-medical industries ranging from electronics and electrical equipment (18%), automotive (7%), science and technology engineering firms (6%) aircraft and aerospace craft (4%), to others such as military technology and applications, insurance, and personal care (13%).

These technological entrants used various modes for investment in bionic technologies. As would be expected, internal investment dominated and was undertaken by 87 % of the firms. This was complemented by other investment modes: 25% of firms sourced technology through alliances, and 16% engaged in acquisitions of other technology investing firms. Moreover, these modes were not mutually exclusive: 23% of the technological entrants used more than one strategy to acquire bionic technology, and 5% of them used up to three different modes of technological investments.

Technological System Integration and Creation of Competencies

We turn to our analyses of the firm's technological integration by utilizing patenting activities. Our analyses of capability development at the component or system level, and of forward citations of patents developed by each firm type are provided in Table 4a (crosstabs) and Table 5 (OLS regressions).[16] The *Integration Dummy* in Table 4a reveals that all incumbents (Mean = 1.00), and most startups (Mean= 0.83) and other established firms (Mean = 0.90) integrated at least two component technologies. However, incumbents integrated more subtechnologies (Mean = 3.28), than both startups (Mean = 2.39) and other established firms (mean = 2.56). These crosstab patterns are robust to multi-variate analysis in Table 5. Here, the coefficients represent the predicted probabilities of other established firms and startups relative to the baseline probability of these strategy for incumbents, which is reflected in the regression constants. In Model 1 (*Integration*

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[16] These analyses are conditional on patents, excluding firms that invested in technology through other channels (e.g., alliance and acquisitions) than patenting.

Dummy), the estimated constant is 1.00 and reflects the population mean of 1 for incumbents in Table 4a). The startup point estimate of -0.18 implies a probability of 0.82 (=1-0.18) which approximates the mean of 0.83 reported in Table 4a. Similarly, the coefficient of -0.12 for other established firms in Model 1 implies a probability of 0.88 (=1-0.12), reflecting the mean of 0.90 for this group in Table 4a. Controlling for the count of prosthetic patents (Model 2) does not meaningfully change this result. If we had prespecified a test of equality of coefficients of other established and startups, we would have failed to reject the null that they are the same ($F_{1,84}=0.88$). The estimates are generally imprecise reflecting the lack of inter-marginal variation on the dependent variable; i.e., almost all firms did some integration in their patent portfolio. The point estimates for *Number of Components Integrated* in Table 5, Models 3-4 similarly mirror the crosstabs in Table 4a. Incumbents integrated across a greater number of sub-technological subsystems relative to startups and established firms. Moreover, a properly pre-specified test of equality of coefficients of other established firms and startups would fail to reject the null ($F_{1,84}$=0.26). Interestingly, the forward citations of patents of each firm type indicate that the knowledge created by each of the firm types were actively built on by others, thus indicating significant spillovers in the knowledge base of actors across the ecosystem. The predictive probabilities in Model 5 map directly onto the unconditional means for each group in Table 4a. Reflective of large standard errors in Table 4a and low inter-marginal variation, the coefficients are not precisely estimated. Model 6 clarifies that an inability to conclude meaningful differences between the groups is not due to different size patent portfolios.

[Tables 4 and 5 about here]

Value Capture Strategies

The crosstabs in Table 4b and multivariate specifications of Table 6 provide results for value capture strategies, which include *Market entry,* additionally separated by *Entry into System* vs. *Component, Being Acquired*, and *Providing Technology In Alliance.* Turning to market entry first, as seen in both Tables, incumbents were more likely to introduce prosthetic end products: 10 of 23 commercialized products and 9 of these 10 were system-level solutions. In stark contrast, both market entry and provision of system level solutions was uncommon for startups and rare for other established firms. In addition to the crosstabs in Table 4b, this is depicted by the point estimates for these firm types relative to the constant estimates in Models 1-6 of Table

6 (reflecting incumbents as the omitted category). Notably, these coefficients are more precise given higher inter-marginal variation in the dependent variable. Adding the constant and the point estimates, Model 1 reveals a 0.21 (=0.52-0.31) probability of startups entering the market, reflecting the fact that only 7 of 33 eventually entered. Model 3 reveals the much lower likelihood of 0.09 (=0.43-0.34) that startups provided entire system solutions, mirroring that 3 of 33 startups entered with system products (rather than component products). Other established firms rarely entered: Model 1 reveals their 0.03 (=0.52-0.49) probability of market entry, reflecting the fact that only 2 of 55 established firms chose this strategy. If we had prespecified test of equality of coefficients of other established and startups, we would reject the null that they are the same ($F_{1,108}$=*5.22*).[17]

In terms of *Being acquired*, Table 4b and Models 7-8 in Table 6 depict higher likelihoods for startups. Adding the constant and the point estimates, Model 7 reveals a 0.33 (=0.13+0.20) probability of startups being acquired, reflecting that 11 of 33 startups were ultimately acquired, 3 of whom had engaged in market entry prior to the acquisition. Table 4b that only 7 of 33 eventually entered. In contrast, *Being Acquired* was a rare event for other established firms: Model 7 reveals a 0.02 (=0.13-0.11) probability of this event, reflecting that only 1 of the 55 other established firms was acquired. If we had prespecified test of equality of coefficients of other established and startups, we would reject the null that they are the same ($F_{1,108}$=*20.25*). Finally, *Providing Technology in Alliance* was also more likely for startups relative to other firm types. From Table 4b, 11 of 33 startups provided their technology to other firms, which translates to the likelihood of 0.33 (=0.20+0.13) in Model 9, Table 6. Interestingly, the provision of technology is the one strategy that other established firms were most likely to employ: 5 of 55 other established firms provided technology in an

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[17] These results are robust to a control for the number of a firm's bionic patents (even numbered columns in Table 6), particularly as one appreciates that the distribution of patenting is highly skewed. Consider that the mean bionic patent portfolio size for startups is 1.3 patents, and the mean for Other Established firms is 2.18. Thus, the Count of Prosthetic Patents coefficient estimate of 0.02 implies a modest predicted change for the mean firm of each type: a 0.03 greater likelihood of market entry for the mean startup (1.3*0.02 = +0.026), and double that for the mean established firm. However, for the established firm with 16 patents (the maximum), the predicted probability is 0.34, which is an order of magnitude larger than the average established firm. For the startup with 7 patents (the maximum), the predicted probability of entry is 0.36, or about 12 percentage points more likely than the mean startup. This basic pattern of association between bionic patent portfolio size and value capture strategies is found for system level market entry (Models 2 and 4), but not necessarily for component entry (Model 6). Nevertheless, the estimates in these models reflect the patterns in the Table 4b crosstabs. The magnitude of the coefficients on Other Established firms relative to the constant in Models 1-6 leads to predicted probabilities near 0 for established firms across these models. This reflects the fact that entry by Other Established firms is rare or did not happen in our sample (see Table 4b).

alliance, which is mirrored by the likelihood of 0.09 (=0.13-0.04) in Model 9, Table 6. Additionally, the small and imprecisely estimated coefficients on Bionic Patents in models 8 and 10 reveal no meaningful differences between high and low patenting firms

The statistical analysis puts the differing patterns of capability development and value capture strategies in sharp relief. On average, incumbents patent portfolios had greater breadth, and they were more likely to enter by providing more complete bionic prosthetic solutions. This suggests that incumbents' know-how complemented the new bionics technology. It also reveals that this strategy was rare for other established firms, and low for startups; the latter commercialized through alliances, sales of components, or were acquired. The statistics also suggest that patenting in bionic prosthetics complements some strategies (e.g., market entry), but not others (being acquired, or providing technology in an alliance). However, the data provide little insight as to whether our explanations are consistent with the field, why some firms patented but not others, and why some chose to enter or form alliances but not others. For this, we turn to an analysis of business histories.

[Table 6 about here]

ANALYSIS OF BUSINESS HISTORIES

Sample Selection and Analytic Method

Guided by scholars utilizing historical methods in strategy and entrepreneurship (Braguinsky & Hounshell, 2016; Bucheli & Wadhwani, 2014; Pillai et al., 2022), we identify 15 historically significant cases in the following manner. We first rank order firms in the above census based on their number of bionic prosthetic patents to ensure inclusion of the most active technological entrants, independent of their eventual economic outcome (*i.e.,* value capture strategy). We then use a stratified sampling approach to identify the top 5 patenting firms from each firm type, given our interest in comparing value creation and capture within and across firm types.[18] For each firm, we conducted a comprehensive search of archival data, including annual reports, corporate websites, LexisNexis and trade magazines (see Appendix Table A7). Appendix Table A4 provide descriptive statistics of our historical sample.

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[18] In instances of ties for the fifth place for patenting activity, we chose the firm that had higher alliances and acquisition activity, or richer records for their actions and rationale.

The above empirical associations provide us the preliminary structure to a deeper historical analysis. From this starting point, we develop each firm's unique historical narrative and compare and contrast among them for both within- and across-firm type pattern generation. We do so by utilizing various historical research practices such as triangulation for data validity, periodization, narrative construction and hermeneutics for explanation and understanding (Braguinsky & Hounshell 2016; Kipping, Wadhwani, & Bucheli 2014; Pillai et al., 2022). Appendix C1 provides additional details on the analytic method. Overall, our inquiry involved multiple iterations between historical records and insights that emerged from the data to ensure that the patterns depicted are based on comprehensive and comparable information across different firms. We also note any observed anomalies or differences observed within- and across- firm types.

The individual firm narratives are provided in Appendix C2, inclusive of source and citations for key data and quotes: for ease of readability and conserving space, we do not include these sources and citations in the main text. Tables 7a-c provide summary descriptions of each firm's prior knowledge context and motivation for technological entry, technological investments for creation of the bionic prosthetic technological system, and value capture strategies.

[Table 7 about here]

Prior Knowledge Context of Technological Entrants

Table 7a documents that all five startups were helmed by at least one founder conducting basic or translational research in academic or hospital settings in advanced prosthetics, biomechtronics, or artificial intelligence. For each, the founders sought to capitalize on their basic research, and in two cases, the founding team included an amputee who sought to address needs unmet by conventional prosthetics. iWalk provides an illustrative example of founder motivation and prior experience influenced why it was created and what was its technological focus. Hugh Herr, lead founder was a prodigy mountain climber who lost his legs to frostbite. Herr subsequently chose a career in engineering, conducting basic research and rising to a leadership position in MIT's media lab over a twenty-five-year period. In the early 2000s, Herr developed and sublicensed his lab's bionic "Rheo Knee" technology to prosthetics incumbent Össur. Partially due to his dissatisfaction of the technology transfer process, Herr founded iWalk in 2006 to consolidate the Rheo Knee license with opportunities arising from a new bionic ankle technology developed in his MIT lab. While the founding team and early recruits in each startup represented complementary technological or user knowledge, none of the founders in four startups had direct experience of prosthetics manufacturing, marketing, or sales. The exception, Orthocare, was created by amputee-lawyer Doug Cormack who convinced bioengineer cofounders Kim Coleman and David Boone to fold their prior venture, Cyma, into Orthocare at its inception. The founders' prior venture provided Orthocare with knowledge in product design, clinical evaluation, regulatory support, transition to manufacturing, and machine design.

Table 7b reveals that four established firms from other industries (Deka, Honda, Kobe Steel, and Samsung) had diverse technological and downstream capabilities related to (auto)motives, electrical engineering, computers, or robotics. For example, Liberty Mutual Insurance lacked prior relevant technological capabilities; but deemed it more economical to develop and fit injured workers with better-performing bionic prosthetics for return to work than to pay long term disability claims. In contrast, Honda and Samsung each had a longstanding strategy of growth and diversification strategy into humanoids or assistive technology, dating back to the 1980s. Kobe Steel had a century long history of medical technology investments through local hospitals and its "keiretsu" group firm affiliations. It was motivated by its collaboration partner, Hyogo Rehabilitation, to make technological investments in bionic prosthetics. Deka was invited by DARPA to participate in its Revolutionizing Prosthetics 2007 grand challenge to help develop upper limb smart prosthesis for wounded veterans through grant funding of $18 million dollars.[19]

All incumbents (Blatchford, Össur, Ottobock, Steeper & Willow Wood) had technological capabilities in mechanical prosthetics (Table 7c). Each had pioneered critical innovations in components elements of materials, alignment designs or mechanical controls. They also possessed downstream capabilities related to marketing, sales, and manufacturing for orthotic and prosthetic devices. In addition, all five firms were specialized in orthotics and prosthetics, rather than being diversified in other medical devices or industries. Each of these incumbents had histories as technological leaders in the industry, though not in bionics. For example, Össur explicitly sought to build on its capabilities in materials, marketing, sales and distribution by "[securing] technological developments" (Össur 2000: 6-7).

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[19] DEKA's pre-existing upstream capabilities in electronics and prior inventions (stair-climbing, self-balancing wheelchair; two wheeled Segway), and perhaps Kamen's reputation, had attracted DARPA's attention.

Technological Investments for Creation of New Bionic Technology Systems and Competencies

Table 7a depicts how startups' technological investments leveraged their founders' research expertise and insights, including through licensing of patents assigned to their academic institutions. Each startup's path-dependent technological investments focused on bionic components through use of computer algorithms, sensors, robotics or artificial intelligence. For example, iWalk's Hugh Herr's built on his insights regarding a need for improvement not only in the human nervous system interface and use of data for enhanced performance, but also in the physical connection to the body. iWalk pieced together these capabilities in its efforts to develop a bionic ankle. Orthocare grew its functionally diverse business and technology team for enhance bionics expertise through a key early acquisition of Martin Bionics and forging ties with and hiring personnel from Johns Hopkins' Advanced Prosthetics Lab. To fill gaps in hydraulics capabilities, it licensed a small hydraulic subtechnology from Oak Ridge National Labs. All five studied startups focused initially on single products, which contrasts with larger firms more diversified strategies.

Table 7b showcases that three of the other established firms' investments in bionic prosthetics technologies (Kobe Steel, Honda, and Samsung) were an offshoot of their development of bionics sub-technological systems for problems other than prostheses. As an example, Honda leveraged existing robotics capabilities developed as part of a human-mobility assistance technology designed to alleviate factory worker fatigue. Honda invested in AI, motion sensing for human mobility starting in 1999, brain-machine interface technology starting in 2007, and experimented with a prototype arm that would allow an amputee to ride a Honda motorcycle. All five firms' investments were fueled by partners with prosthetics related capabilities and motivations. For example, as an early entrant in 1961, Liberty Mutual funded basic research in universities and subsequently hired several of these researchers to internally develop the "Boston Elbow" in the 1960s. Similarly, Deka's development of system prototypes heavily relied on a consortium of university labs and rehabilitation centers.

All five incumbents developed and sourced bionics knowledge and combined it with their own capabilities in traditional prosthetics subtechnologies such as materials, hydraulics and prosthetic design (Table 7c). Some built on their historical investments, such as Ottobock in powered limbs and Steeper in electric/battery powered hands and hooks. To complement internal knowledge, each engaged in a deliberate strategy to acquire startups and partner with universities, startups, and other established firms. In particular, Blatchford, Össur, Ottobock explicitly note this as their technology strategy and Willow Wood had a robust CVC program. For example, Össur (1999:7) stated developing new bionic technology "*through internal development and strategic investment in other companies*" and especially by looking for "*small firms with only one product line [who] will find it increasingly more difficult to comply with official regulations while conducting research and development.*"[20] Many, if not all, leveraged internal knowledge related to clinical testing, fitting, and customer engagement to increase effectiveness of prototypes and move the technologies into development and application stages, though Ottobock also acquired several companies that specialized in fitting and clinical tests.

Figure 4 provides a visualization of each of the 15 firms in our historical sample as a node, and licenses, alliances, and acquisitions as ties across them and other actors.[21] Taken together with the documented relationships in Tables 7a-c, it shows the internal technological investments of each of the fifteen firms in our historical sample leveraged non-market collaborative networks and market channels to create bionic prosthetics technological systems. Several interrelated insights emerge from the historical analyses represented in Table 7 and Figure 4. First, from a capability perspective, the knowledge of various components was distributed across numerous actors. Startups, other established firms, and incumbents in our historical sample (the red circles) not only leveraged each other's knowledge and capabilities, but also that generated by at least 33 other firms (yellow circles) and 39 universities, rehabilitation centers/clinics or government programs (gray squares). Second, the historical analysis reveals that in addition to "science-push" investment by inventors and firms with requisite capabilities, the clusters represent fostering of technological investments through "demand pull" engagement by users with unmet needs, ranging from amputees (e.g. Herr, McCormack) to firms (e.g. Liberty Mutual) to public agencies (e.g. DARPA's 2007 & 2009 Revolutionizing Prosthetics Challenges).

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[20] For example, Otto Bock with perhaps the most extensive sourcing strategy of the five studied incumbents, partnered with companies with electronics expertise in the late 1960s, the University of Alberta in 1992, developed a bionic knee in 1997, licensed neurostimulation technology from startup Victhom in 2005 (later acquiring this division in 2012). Otto Bock also developed materials capabilities by partnering acquiring two companies with carbon fiber expertise in 2001 and 2017. Otto Bock stood out in that it acquired three fitting technology companies (1998, 2003, 2013) and also used acquisitions to expand its manufacturing capabilities in 2002 and sales and distribution (into pediatrics) in 2005. Additional Otto Bock acquisitions and partnerships are listed in the Table 7b and described in Appendix C2.

[21] The direction of the arrows do not necessarily imply a unidirectional flow of knowledge in each case.

[Figure 4 about here]

Third, within each of the technology clusters of Figure 4, some relationships were based upon one party building on another's knowledge (often through market-based licensing or acquisition), while others represented active co-development and alliances that brought complementary knowledge and component technologies together. These "small-world" clusters reveal path-dependencies that link the actors' prior knowledge and affiliations to their choices of technological investments and collaborative relationships. Fourth, within each cluster, the technological system was created through continued investments in improving all components. Here, startups spawned from research institutions. All firms created critical component knowledge, early "system" prototypes, and patents. Fifth, incumbents played a key role in technology convergence and creation of usable applications from prototypes. Their R&D efforts consisted of both "upstream research" initiatives for integration of "old" and "new" technologies to create entire technological systems, and "downstream development" initiatives that transformed basic research and prototypes of other actors into effective and usable applications, through additional integration of materials, mechanical and design innovations.

Value Capture Strategies in Bionic Prosthetics Industry

Table 7a highlights that one startup, Orthocare, first sought to capture value by commercializing components (Compas). Two startups, iWalk and Touch Bionics, launched complete products (BiOM Ankle, i-Limb). However, licensing and alliances (often with different incumbents) were dominant forms of value capture for iWalk, Orthocare and Victhom. Moreover, only Orthocare, the sole startup with a founder with operational and marketing experience, remains independent. All startups ultimately sought acquisition (four incumbent prosthetic firms and one established firm were on the "buy" side of these transactions). Notably, Motion Control's acquisition by an incumbent occurred in 1997, the year of the industry's inception.

Among other established firms, two (Honda, Samsung) have no record of market entry, alliances, or divestitures of capabilities to date. Only DEKA entered the market, doing so by leveraging downstream capabilities of startup Mobius Bionics to commercialize its Luke Arm prototype and targeting DoD and VA users (given initial funding from DARPA). Kobe Steel licensed its technology to incumbent Blatchford and Nabco, a diversifying entrant into bionic prosthetics with keiretsu group affiliation with Kobe. Liberty

Mutual, the earliest of technology entrants, sold parts of its prosthetic research division to employee Bill Hanson's spinout Liberating Technologies before shutting down its research center in 2017. Remarkably, all five other established firms' patents were extensively cited in follow-on bionic prosthetic patents.

All five incumbents in our sample entered bionic prosthetics: three with functional bionic limbs, and two providing bionic accessories. Otto Bock commercialized the C-leg bionic prosthetic for industry inception in 1997(aided by technology licensed from startups Biomech and Victhom), and Blatchford followed shortly thereafter with their Intelligent Prosthesis+/Adaptive Prostheses that built on licenses of Kobe Steel's patents. This pattern also holds for market entry of the other incumbents in the historical sample: each commercialized functional systems that were created by integrating component knowledge or honing/further developing technologies and prototypes created by startups or individual inventors. Within this process, the individual firm histories reported in Appendix C2 reveals that the incumbents' downstream capabilities related to clinical testing, regulatory approvals, production and marketing/sales were important to create products that optimized across tradeoffs encountered in functionality and use of their innovations.

DISCUSSION & CONCLUSION

Our conceptual framework began by distinguishing between two prevailing definitions of radical technology: one based on economic effects of a technology on incumbents, and the other based on novel base principles. When considering both in tandem, each revealed an important gap in the other. Specifically, a predominant focus on incumbent-entrant dynamics post industry inception conflates economic effects and prior organizational history in the definition of a radical technology. The definition of technological systems using novel base principles focuses on configuration of architectures from component knowledge, but abstracts away from microprocesses undertaken by heterogenous firms to create radical technologies and subsequently capture value. Our process model relied on the novel base principles definition to provide insights about how heterogeneous actors may make component and system level technological investments to build competencies and incubate a radical technology, and how and why they may pursue different value capture strategies that influenced the ensuing industry structure.

The accompanying abductive study of the bionic prosthetics industry is illustrative of this process: the quantitative analysis describes a decades-long process of technology incubation and creation of competencies and the historical analysis elucidates the purpose and logic of this co-evolutionary process. For technology incubation, our analyses reveal the creation of bionic prosthetics required both new knowledge of bionic controls, the utilization of digital vs. mechanical base principles and the integration of bionics into useful prosthetics through the development of, and recombination with, complementary subtechnologies (Arthur, 2009; Baldwin & Clark, 2000; Rosenberg, 1963). Such technology incubation required simultaneous creation of firm-level competencies that built on prior histories through technological investments and creation and reconfiguration of capabilities within startups, incumbents and other established firms. This coevolution occurred within a vibrant ecosystem during and post incubation period (Moeen & Agarwal, 2017), wherein all three firm types played important and complementary roles. These roles also had implications for their value-capture strategies. Startups—largely hailing from academic institutions—infused the new industry with cutting-edge technology based on novel scientific principles and subsequently traded with, and integrated into the conventional prosthetic manufacturers. Knowledge was created by other established firms, but they rarely entered or traded within the bionic prosthetic market. Incumbents actively developed component technologies and integrated these into systems, leveraging knowledge from research labs and other firms through alliances and acquisitions to dominate market entry and commercialization.

The observed "dominance by birthright" of incumbents in markets for commercialization of bionic prosthetics runs counter to existing studies extolling and sampling on radical technologies introduced by entrants—startups and diversifying entrants alike. The lack of "disruption" to the incumbent group in the face of a radical technology is puzzling under the "economic-effects" definition, but consistent with our process model based on the "novel principles" definition. Notably, it was only by studying the incubation period that we were able to approach a satisfactory explanation of firm strategies for value capture. Bionic prosthetics were created by incorporating novel electronic and artificial intelligence principles with reconfigurations in mechanics, materials, and design components through recursive problem-solving. Our statistical results clarify that, on average, both startups and other established firm invested in upstream research and in relatively focused ways compared to incumbents. These firm types lacked what incumbents possessed: prior knowledge and continued technological investments developing bionics, mechanical, materials and design subtechnologies. Moreover, incumbents were better able to integrate across subtechnologies to create functional and usable bionic prosthetic systems; such technological integration coupled with downstream (non-technological) complementary capabilities was key to their pursuing product market commercialization as a value capture strategy. Thus, our contextual deep dive helps explain why bionics, a radical new principle, obsolesced neither incumbent capabilities nor market positions in prosthetics. Moreover, it reveals the importance of collaborative rather than competitive incumbent-entrant dynamics within vibrant technological ecosystems. From the perspective of the startups, no single strategy was best. Industry census level statistical results indicate that even startups with pioneering bionic innovations found it beneficial to partner and co-develop with incumbents, and eventually be absorbed into the larger product portfolios of incumbents. Market entry, alliances or acquisitions as startup modes of (sequential) value capture hinged on founder knowledge and capabilities, as well as timing. Established firms in other industries who invested in the technological system chose *not* to become diversifying entrants, eschewing market entry in bionic prosthetics in favor of alternative adjacent market opportunities. They also made limited use of licensing and alliances for value capture even though there were significant spillover benefits of their investments, as evidenced by citations of their patents by bionic prosthetics focused firms.

We leave some questions for future research. For example, we do not examine the role of cognition (Tripsas & Gavetti, 2000; Eggers & Kaplan, 2009), nor why all incumbents in conventional prosthetics did not invest in bionics. When and how cognition interacts with capability development is deserving of future examination. Also, our paper does not discern or rank-order among the strategies for value capture in terms of relative shares of value creation. Importantly, we do not claim that there are no conditions under which incumbents could be disrupted, even if they possess relevant capabilities. Conceptually, we would expect to see similar patterns in industries where the application of technologically radical components requires the development and reconfiguration of complementary subtechnological knowhow and solutions in a way that disadvantages entrants, particularly startups. Conversely, we expect to see more disruption where the application of radical technologies does not require the solution to include subtechnological problems in which incumbents have expertise. Given that we explore a single industry, however, we are not able to isolate these mechanisms from idiosyncratic factors at play in determining observed outcomes. For example, the bionics market is limited by the size of the amputee population, and, in the United States, by regulation and insurance reimbursements for expensive bionics. A larger market prize, alternative regulatory regimes or pricing structures may have led to greater investment and entry, inducing startups or other established firms to build up missing capabilities and commercialize products. Alternatively, how new base principles are recombined with existing subtechnologies may also create differences. For example, incumbent hybridization technological capabilities retained value in agricultural biotechnology only as "prior stock" of elite crop varieties, but was completely displaced by biotechnology principles for future plant breeding capabilities, which resulted in market dominance by established firms in other industries (Moeen & Agarwal, 2017). Engagement in the context would help identify important boundary conditions on how technological and market inducements affect incumbent-entrant dynamics in creating and capturing value from radical technologies, and help strategic decision-makers formulate relevant questions in the application of the framework to other settings.

In creating and examining our conceptual framework that unites the nature of radical technologies with microprocesses undertaken by heterogeneous actors to create them, we make several contributions to received literature. First, we highlight key limitations in existing industry evolution literature on *competitive* incumbent-entrant dynamics (Agarwal, Sarkar & Echambadi, 2002; Mitchell, 1991; Klepper, 1996). Much of this literature utilizes the economic effects definition of radical technology (Arrow, 1962; Henderson, 1993; Tushman & Anderson, 1986). Scholars note how downstream complementary assets (Teece, 1986; Gans & Stern, 2000) may buffer incumbents from pioneering entrants (Mitchell, 1989) or enable value appropriation from their technological capabilities (Tripsas, 1997) through follow-on incumbent adaptation (Eggers & Park, 2018). While not discounting the importance of downstream capabilities, our use of a knowledge recombination perspective (Xiao et al., 2021) for the development of a radical technological *system* (Arthur, 2009; Henderson & Clark, 1990), coupled with our findings in bionic prosthetics, suggest that incumbents' knowledge of other relevant subtechnologies and ability to integrate these with the radical component is critical for *both* value creation and capture. Alternatively, Conti, Gambardella, and Novelli (2019) illustrate that for general purpose technologies such as lasers, a firm's choice of specializing in upstream technology markets or entering downstream market applications depends on both application market sizes and presence of downstream capabilities within an application market. Our analysis suggests that creation and application of general-purpose technologies such as bionics will also likely be a function of the absolute and relative cost of acquiring elements of the technological system to serve application markets, including complementary upstream technological capabilities such as old prosthetic technology in our research context. These important findings showcase that the strategic implication of particular component technologies, radical or otherwise, can be better understood through the lens of the nature of technological systems (see also Goldfarb & Kirsch, 2021), and by examining industry incubation efforts rather than a focus on post industry inception competitive dynamics (see also Moeen et al., 2020). This failure to consider the nature of technological systems, and path-dependencies in the distribution and development of capabilities may also shed light on why the theory of disruption does a poor job in explaining firm outcomes (King & Baatartogtokh, 2015). For example, digital photography was radical relative to chemical-based film. But less so in terms of cameras. This may help explain why, in part, companies with chemical expertise such as Eastman Kodak, Kyocera, and Fuji all exited the film market, while camera companies such as Nikon and Minolta each retain presence.

Furthermore, our findings extend the notion of "entrepreneurship in the large corporation" (Ahuja & Lampert, 2001; Katila & Ahuja, 2002), as well as "recombinant capabilities" (Fleming, 2001; Arthur 2009; Yayavaram & Ahuja, 2008). The literature on incumbent-led innovation abstracts away from the industry lifecycle aspects (Xiao et al., 2021). 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 is necessary to create solution systems. By highlighting the nature of technical change and focusing on the nascent period of the industry, we connect the literature to the macro-level conditions under which entrepreneurship in the large corporation may become salient, and also confirm that such efforts may be particularly advantageous when the recombination of old and new technology is useful.

An implication of the technological systems approach and its focus on a technology's role in solving problems is that allows one to harmonize these abovementioned views by expanding the definition of technology from material objects to include the organizational and social elements of a system required to create a useful solution to a problem (Arthur, 2009; Goldfarb & Kirsch, 2021). In this view, Teecian "complementary assets" are a class of related "sub-technologies" similar to how hydraulics was a key sub-technology in the present application. Whether or not one wishes to take this view, our results clarify that the organizational and technological elements were similar in effect. The location of complementary knowledge and capabilities necessary to make prosthetics useful were both technological and organizational, and *both* constrained strategic choice in similar ways. Thus, our process model of co-creation of radical technologies and competencies extends the "profiting from innovation" framework for the first order value creation, rather than relegating it to only value capture (Teece, 1986; Gans & Stern, 2000). Moreover, it highlights how prehistories of both firms and technologies create pathdependencies that constrain and influence entrepreneurial firm strategies (Gans, Stern & Wu, 2019).

In sum, our study explored the benefits of adopting a "nature of technological system" approach to defining radical technology, distinguishing the definition from where the capabilities reside or the organization of the economic system that employs it. This enabled us to create a general framework that incorporates the prior contexts and strategic considerations of the heterogenous firms who developed and deployed radical technological systems to incubate a new industry. Our application of this framework within bionic prosthetics approach showcases that incumbent-entrant dynamics and value capture outcomes requires a contextual understanding of the nature of the technological system and its development through internal investments and trade within collaborative networks.

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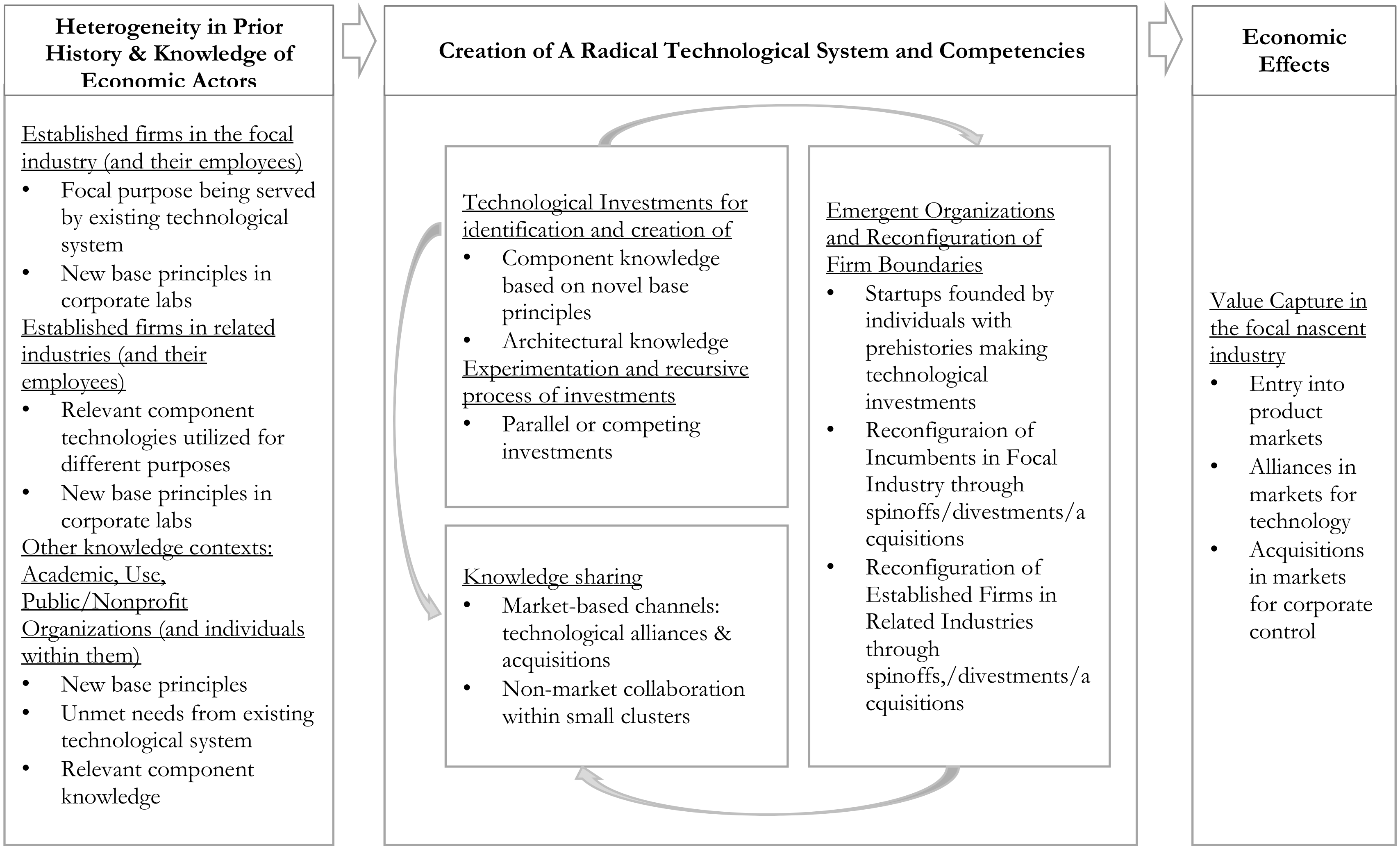
FIGURES AND TABLES

Figure 1: Process Model Linking Prior Histories of Economic Actors to Creation of Radical Technological Systems and Competencies for Subsequent Modes of Value Capture



Heterogeneity in Prior History & Knowledge of Economic Actors

Established firms in the focal industry (and their employees)
- Focal purpose being served by existing technological system
- New base principles in corporate labs

Established firms in related industries (and their employees)
- Relevant component technologies utilized for different purposes
- New base principles in corporate labs

Other knowledge contexts: Academic, Use, Public/Nonprofit Organizations (and individuals within them)
- New base principles
- Unmet needs from existing technological system
- Relevant component knowledge

Creation of A Radical Technological System and Competencies

Technological Investments for identification and creation of
- Component knowledge based on novel base principles
- Architectural knowledge

Experimentation and recursive process of investments
- Parallel or competing investments

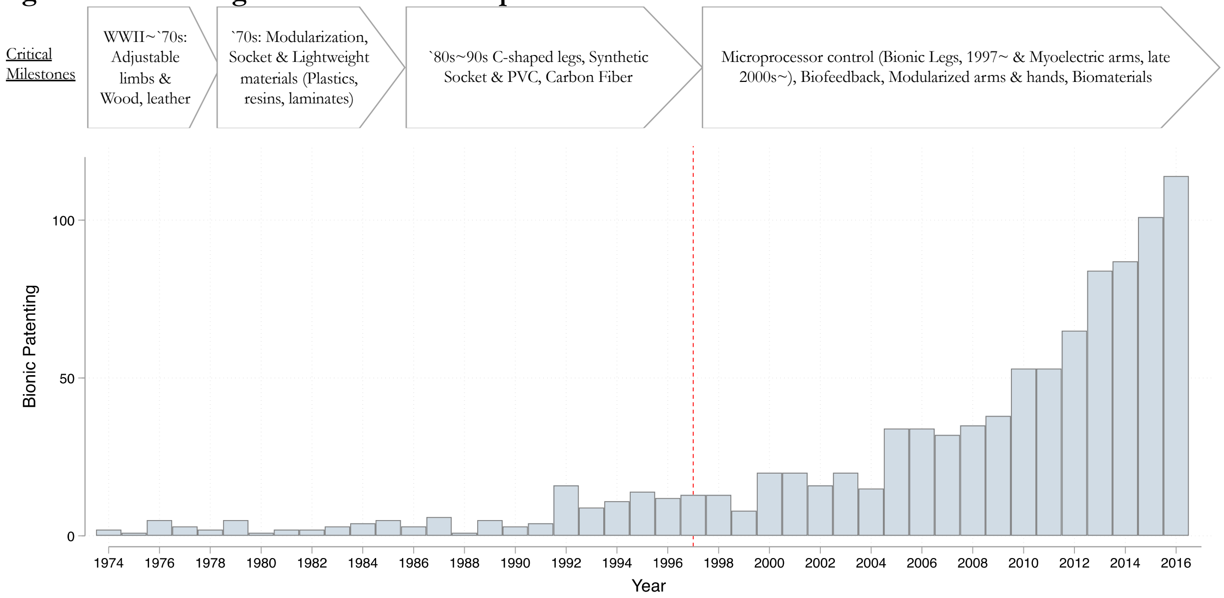
Knowledge sharing
- Market-based channels: technological alliances & acquisitions
- Non-market collaboration within small clusters

Emergent Organizations and Reconfiguration of Firm Boundaries
- Startups founded by individuals with prehistories making technological investments
- Reconfiguraion of Incumbents in Focal Industry through spinoffs/divestments/acquisitions
- Reconfiguration of Established Firms in Related Industries through spinoffs,/divestments/acquisitions

Economic Effects

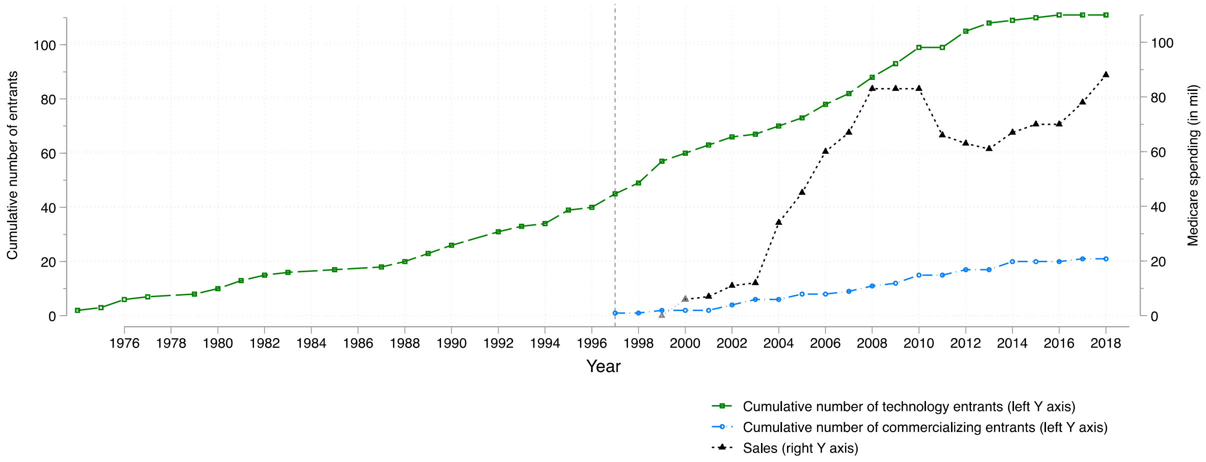
Value Capture in the focal nascent industry
- Entry into product markets
- Alliances in markets for technology
- Acquisitions in markets for corporate control

Figure 2: Technological evolution of the prosthetic limbs



The figure represents the count of granted and pending patent applications made to USPTO by their filing year that are relevant to key bionic prosthetic technology based on Rows (a) and (b) in Table A2. The applicants of the patents include various actors, including firms, non-profit organizations, government agency, and individual inventors.

Figure 3: Firm & Sales Trends in bionic prosthetic limbs



The left Y-axis represents the cumulative count of entrants. The right Y-axis represents sales (Unit: USD in mil.). The trends in sales are estimated by allowed charges for Medicare Healthcare Common Procedure Coding System (HCPCS) codes frequently associated with bionic prosthetic limb reimbursement, using the US Medicare National Part B spending data during 2000-2018 (www.cms.gov). The sharp decrease between 2011-2013 in Medicare spending are due to stringent Medicare audits rather the contraction of the market demand.

Figure 4: Technological ecosystem for value creation

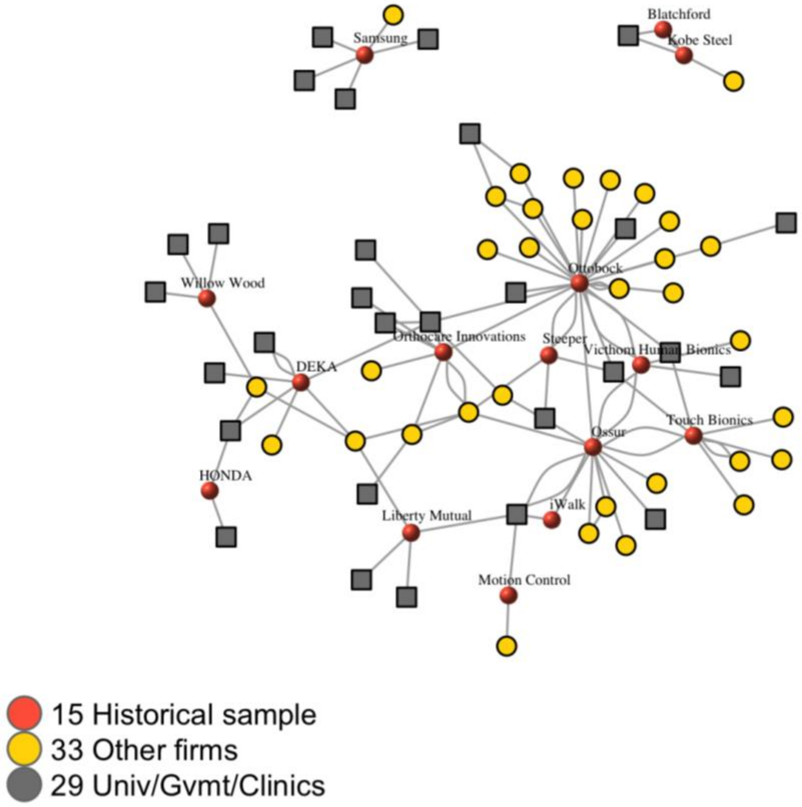


Table 1: Comparison between the conventional prosthetics and the bionic prosthetics

Subtechnological system	Mechanical Prosthetics	Bionic Prosthetics	
		Differences	Similarities
Control	Mechanical controls only: Body powered, pneumatics (air) or hydraulics (liquid) controls Cables and harness-based control using body movement Springs for energy regain Rubber as shock absorbers Hinges with a brake and locks to stop and stabilize movement	Bioelectric Controls: Electric powered with lithium batteries and motors Microprocessor controlled, Myoelectric controlled (muscle signals), Mind-controlled (the central nervous system) Sensors and artificial intelligence for real-time motion analysis Sensory feedback systems the sense of touch and warmth	Integrating mechanical controls into bioelectric controls Pneumatics, hydraulics, hinges
Design	Modularization of customization and interchangeability Special shaped limbs for specific activities: C-shaped leg for running; Swimming legs, Wrench hands for heavy duty work Simpler designs: A hook-shaped hand with voluntary opening Lifelike passive prosthetics and covering	Human Computer Interface: Osseointegration that enables neural connection and sensory feedback Sockets with electromyography sensors Complex design: A hand with individual fingers and more joints	Modularization of parts Sockets and liners Mimicking human anatomy Aesthetic covering
Materials	Lightweight, weight-bearing, energy-restoring materials Metallics (Steel, Aluminum, Titanium) and composites (plastics, resins, laminates, Carbon fiber, silicone)	Electromagnetic composites Biocompatible materials Flexible, thin, tactile skins	Lightweight, weight-bearing, energy-restoring materials Composites (Carbon fiber, plastics, resins, laminates, silicone)

Table 2: Key constructs and data sources

Constructs	Measures (Data sources)
Incumbent	1 if producing any prosthetic limbs before technological entry; 0 otherwise
Other est. firm	1 if an established firm in other industries before technological entry; 0 otherwise
Startup	1 if no business history in other industries before technological entry; 0 otherwise Data sources for firm type: FDA Medical Device Register and Listing Database (2004-2017); Medical Device Register and Listings (1984-2013); Corporate websites
Year of founding	The firm's establishment year Data sources: Bloomberg; Crunchbase Corporate websites; LexisNexis

Table 2 (Cont'd)

Constructs	Measures/Data sources
Technological entry	The firm's first technological investment in the form of either internal R&D or other market mechanisms. • Technological entry by internal R&Ds: filing patents and clinical trials • Technological entry by market mechanisms: collaborative R&Ds, licensing, patent acquisition, and division-/firm-level acquisitions Data sources: Patenting (PatentsView; Patseer); Other internal R&Ds (LexisNexis; The O&P Edge; O&P Almanac; ClinicalTrials.gov); Acquisition & Alliances (SDC; LexisNexi; O&P Edge & O&P Almanac; Corporate websites)
Bionic prosthetic patents	Count of patents that belong to bionic prosthetic technology classes*
Non-bionic prosthetic patents	Count of patents that belong to prosthetic material, design, and mechanical tech*
Forward citations	Count of forward citations of bionic prosthetic patents made by other technological entrants' bionic prosthetic patents*
Firm-level technological integration	Indicator, 1 if the firm filed patents that belong to bionic prosthetic tech classes and also possess patents that belong to prosthetic material, design, and mechanical tech*
Count of Firm-level Technology Integration	The number of bionic prosthetics' subtechnological systems represented in the firm's patent portfolio*
Value capture: Market entry	Indicator, 1 if the focal firm produces bionic limbs; 0 otherwise • Entry into system: the product is an integrated prosthesis ready for fitting (e.g., ankle, knee, arm, and hand) • Entry into component: the product is a part of the system level product or an accessory (e.g., electrodes, software, pattern recognition device) Data sources: O&P Almanac;the 1950s-2018, the O&P Edge (2001-2018), Corporate websites, LexisNexis
Value capture: Being acquired	1 if the focal firm or the prosthetic business of the firm was acquired Data sources: The SDC, Corporate websites; O&P Edge, O&P Almanac, LexisNexis
Value capture: Providing technology in alliance	1 if the focal firm makes profits by licensing its technology or sales of patents Data sources: The SDC, Corporate websites; O&P Edge, O&P Almanac, LexisNexis

* The data source for patent-based measures is PatentsView; Our search included the current FDA registration and listing for medical device firms and the Wayback Machine for FDA's historical Internet archives.

Table 3: Firm-level descriptive Statistics

VARIABLES	N	Mean	S.D.	Min	p50	Max
Incumbent	111	0.207	0.407	0	0	1
Startup	111	0.297	0.459	0	0	1
Other established firm	111	0.495	0.502	0	0	1
Year of founding	98	1965	43.89	1856	1984	2015
Year of technological entry	111	1998	10.95	1974	1999	2016
Tech entry via internal R&D, dummy	111	0.874	0.333	0	1	1
Tech entry via alliance, dummy	111	0.252	0.436	0	0	1
Tech entry via acquisition	111	0.162	0.370	0	0	1

Table 3 (Cont'd)

VARIABLES	N	Mean	S.D.	Min	p50	Max
Bionic prosthetic patents	111	2.153	2.988	0	1	16
Non-bionic prosthetic patents	111	2.721	7.628	0	0	47
Forward cites by tech entrants'	92	11.72	21.79	0	1.33	90
Forward cites by any patents	92	77.47	159.8	1	29.35	1185
Firm-level technological integration	89	0.899	0.303	0	1	1
Count of Firm-level Technology Integration	89	2.663	0.865	1	3	4
Value capture: market entry	111	0.189	0.393	0	0	1
Entry into system	111	0.135	0.343	0	0	1
Entry into component	111	0.072	0.260	0	0	1
Value capture: being acquired	111	0.162	0.370	0	0	1
Value capture: providing technology in alliance	111	0.171	0.378	0	0	1

See Table A3 in Appendix for descriptive statistics by firm type and the matrix of correlations; Patent based measures are calculated conditional on patenting activities.

Table 4 (a) Capability development by firm type

	Incumbent						Startup						Other established firms					
Variable	N	Mean	SD	Min	p50	Max	N	Mean	SD	Min	p50	Max	N	Mean	SD	Min	p50	Max
Bionic prosthetic patents	23	3.3	3.1	0	2	12	33	1.3	1.6	0	1	7	55	2.2	3.4	0	1	16
Mean forward cites by tech entrants	20	10.8	21.4	0	2.0	83.5	23	7.3	18.5	0	1	87	48	14.2	23.4	0	1	90
Integration, dummy	18	1	0	1	1	1	23	0.8	0.4	0	1	1	48	0.9	0.3	0	1	1
Number of subtechnologies integrated	18	3.3	0.7	2	3	4	23	2.4	0.8	1	3	4	48	2.6	0.9	1	3	4

Additional statistics by firm type are presented in Appendix Table A3.

Table 4 (b) Value capture strategy by firm type

	N	Market Entry: (a) or(b)	(a) Entry - system level	(b) Initial entry - component	Ever being acquired	Acquired after market entry	Providing technology in alliance
Incumbent	23	10	9	2	3	1	3
Startup	33	7	3	5	11	3	11
Other est.	55	2	2	0	1	0	5
Total	111	19	14	7	15	4	7

Columns (a) and (b) are not mutually exclusive in that two firms entered at both system and component levels.

Table 5: Dependent Variable – Technological Integration, OLS

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	System Integration, dummy		# of components integrated		Forward citation by tech entrants of patents by	
Startup	-0.18 (0.10)	-0.15 (0.11)	-0.87 (0.27)	-0.47 (0.29)	-3.47 (6.68)	-5.52 (6.92)
Other established firms	-0.12 (0.09)	-0.08 (0.10)	-0.77 (0.24)	-0.36 (0.25)	3.40 (5.80)	0.26 (6.13)
Count of prosthetic patents		0.002 (0.003)		0.03 (0.01)		-0.25 (0.20)
Forward citations by any patents						0.01 (0.01)
Constant	1.00 (0.07)	0.96 (0.09)	3.28 (0.20)	2.82 (0.24)	10.78 (4.88)	13.38 (5.60)
Observations	89	88	89	88	92	92
R-squared	0.04	0.04	0.13	0.21	0.02	0.04
$\beta_{startup} = \beta_{other\ est.}$	.54	.88	.21	.26	1.55	1.05
F-Stat	1.704	1.309	6.344	7.500	0.797	1.012

Firm-level analysis. Standard errors in parentheses. The baseline group is the incumbent group. The row, $\beta_{startup} = \beta_{other\ est.}$ reports F-statistics for differences across these firm types. For Models 5-6, the number of bionic prosthetics internally developed and the mean count of forward citations to any patents are controls. Note that the estimations are conditional on patenting, excluding firms entering without any patents.

Table 6: Dependent Variable – Value Capture Strategy, Linear Probability Model

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
VARIABLES	Market entry		Entry into system		Entry into component		Being acquired		Providing tech. in alliance	
Other established.	-0.49 (0.09)	-0.47 (0.09)	-0.40 (0.08)	-0.38 (0.08)	-0.13 (0.06)	-0.12 (0.06)	-0.11 (0.08)	-0.11 (0.08)	-0.04 (0.09)	-0.03 (0.09)
Startup	-0.31 (0.09)	-0.27 (0.10)	-0.34 (0.08)	-0.31 (0.09)	0.02 (0.07)	0.04 (0.07)	0.20 (0.09)	0.21 (0.09)	0.20 (0.10)	0.22 (0.10)
Bionic patents, count		0.02 (0.01)		0.02 (0.01)		0.01 (0.01)		0.00 (0.01)		0.01 (0.01)
Constant	0.52 (0.07)	0.46 (0.08)	0.43 (0.06)	0.38 (0.07)	0.13 (0.05)	0.10 (0.06)	0.13 (0.07)	0.12 (0.07)	0.13 (0.08)	0.09 (0.09)
Observations	111	111	111	111	111	111	111	111	111	111
R-squared	0.23	0.24	0.21	0.22	0.08	0.09	0.16	0.16	0.08	0.09
$\beta_{other\ est.} = \beta_{startup}$	5.22	6.19	.64	1.00	7.46	8.26	20.25	20.03	9.04	9.61
F-Stat	15.75	11.54	13.97	10.31	4.511	3.539	10.13	6.71	4.70	3.4

Standard errors in parentheses. The baseline group is the incumbent group. The row, $\beta_{other\ est.} = \beta_{startup}$, reports F-statistics for differences across these firm types.

Table 7a: Historical Analysis of Startup Sample

Name (Year of Founding)	Founder Knowledge Context/Motivation	Key Technological Investments and Creation of Technological System (year)	Value Capture Strategies in Prosthetics
iWalk (2007)	• Hugh Herr, amputee professor, Biomechatronics research group at MIT o Prior experience of developing Rheo knee with Ossur (2000-2004) o Maintained dual appointment with MIT; created firm to reduce technology transfer inefficiencies • Nicholas Negroponte, MIT Media lab; Richard Greenwald, Bioengineering Dartmouth	• Developed bionic ankle BiOM (by licensing MIT technology at founding) (2007-2010) • Developed algorithms for analyzing user surroundings, gait optimization (2007-2017) • Created architectural design for motor, sensor and spring components (system) (2007-2017) • Developed neural interface using targeted muscle reinnervation for lower limb device controls (2007-2017)	• iWalk utilized revenues from Herr's license of Rheo knee technology to Ossur (Incumbent) (2005) • Entered market with BiOM ankle (Announced 2008; Available in 2010); reimbursed by DOD and VA • Acquired by Ottobock (Incumbent) (2017)
Motion Control (1974)	• Stephen Jacobsen, PhD at MIT (Adviser: Prof. Mann of Boston Arm); Bioengineering Professor at University of Utah (UU) o Developed technology for artificial arm, heart, and kidney • Motivated to develop Jacobsen's invention at UU	• Developed upper-limb (UL) prosthetics technology by licensing UU technology (1974-1997) • Developed myoelectric control system for UL prosthetics (1974-1997) • Created Utah Artificial Arm in 1981, and improved version the Utah Arm 2 in 1997 (system) (1974-1997)	• Acquired by Fillauer Companies, Inc. (Incumbent) in 1997
Orthocare Innovations (2007)	• Doug McCormack, an amputee lawyer • Cofounders through Cyma acquisition: Kim Coleman, prior founder/director of research of Cyma; David Boone, director of research at Cyma • Motivated to translate cutting-edge technology into commercial products	• Created iPed, a computer-controlled prosthesis (2008-2010) o Acquired Martin Bionics, academic startup after McCormack met Jay Martin as his prosthetist patient at Sabolich; Martin continued within Orthocare o Partnered with College Park industries for the iPed development • Developed components for robotic arm (2008) o Participated in DARPA's 2009 Revolutionizing Prosthetics (2008) o Licensed small-scale hydraulic technology from Oak Ridge National Lab (2009) o Collaborated with Johns Hopkins' APL for robotic arm development (2008)	• Entered market with Compas (component) (2009) • Licensed iPED to College Park Industries (Incumbent) (estimated around 2012) • Partnered with Ottobock to commercialize a bionic ankle Magellan (2013)

Table 7a (Cont'd)

Name (Year of Founding)	Founder Knowledge Context/Motivation	Key Technological Investments and Creation of Technological System (year)	Value Capture Strategies in Prosthetics
Touch Bionics (2005)	• David Gow, clinical director, NHS, UK o Specialized in rehabilitation engineering services and powered upper limb research and development • Motivated to address the lack of product variety and technological progress and to commercialize Gow's inventions at the NHS	• Utilized Gow's bionic inventions i-Limb and i-Limb digits in NHS (2005-2009) o Partnered with clinical partners at launch and onward including Advanced Arm Dynamics, Benchmark Orthotics and Prosthetics, Hanger Prosthetics, LIVING SKIN, Sabolich Prosthetics and Research o Partnered with LIVINGSKIN and ARTech for high definition covering solutions o Acquired LIVINGSKIN for covering resembling the dermal layers of natural skin (2008) • Developed a bionic arm system and functional upper limb components (e.g., individually controllable digits) (2005)	• Entered market with i-Limb (2007) • Launched i-Limb digits (2009); Biosim (software tool) (2010) • Acquired by Ossur (2016)
Victhom Human Bionics (2002)	• Stephane Bedard, PhD in bioengineering at Laval University o Dissertation focused on AI applications to bionic leg • Motivated to apply Bedard's AI research to bionic leg products	• Utilized Bedard's AI research to develop bionic leg operations o Acquired Neurostream for its neurostimulation technology (2004) • Developed a bionic product line including the Power Knee for 3-6 years (2003; 2005) o Codeveloped with Ossur	• Licensed Power Knee technology to Ossur (2004) • JV with Ottobock to commercialize neurostimulation (2009) • Sold Neurostream to Ottobock (2011) • Acquired by Ergoresearch (Other established firm) (2013)

Table 7b: Historical Analysis of Established Firms in Other Industries Sample

Firm Name (TE year)	Firm Knowledge Context and Motivation	Key Technological Investments and Participation in Knowledge Aggregation (year)	Value Capture Strategies in Prosthetics
DEKA (2006)	• R&D firm in medical devices and personal mobility (Segway; iBOT wheelchair) o Invited to participate in DARPA's Revolutionizing Prosthetic Project to develop bionic arm system for wounded veterans (2006)	• Developed a system level prototype and components including the neural interface and actuators (2006-2009) o Partnered with Liberating Technologies (LTI), Rehab Institute of Chicago (RIC), UNB, Northwestern, etc. • Entered clinical trials and improved usability for prosthetic arm for FDA approval (2009-2014) o Collaboration with VA	• Partnered with Mobius Bionics (Startup) in 2016 to commercialize the DEKA Arm (Luke Arm) developed in the DARPA's RP project o Initial sales largely purchased by DoD/VA

Table 7b (Cont'd)

Firm Name (TE year)	Firm Knowledge Context and Motivation	Key Technological Investments and Participation in Knowledge Aggregation (year)	Value Capture Strategies in Prosthetics
Honda (1999)	• Diversified businesses in automotives, motorcycles, engines; power equipment o Prior knowledge in humanoid robots including ASIMO (the 1980s) • Motivated by bionics R&D strategy (1999) o Vied to develop assistive technology for the elderly/disabled by leveraging automobile and humanoid technology o human-mobility assistance to alleviate worker fatigue	• Applied existing automobile and robot technology to develop artificial intelligence, control CPUs, motion sensing tech, battery, etc. for human mobility (1999-) • Developed brain-machine interface technology (2007) o Partnered with Advanced Telecommunications Research Institute International • Developed/tested control systems for walking (2008-2018) o Partnered with Shinseikai Medical (2008) and RIC(2014) • Developed bionic motorcycle arm prototype for amputees for communication between rider and bike (the 2010s)	• No value capture in prosthetics industry to date
Kobe Steel (early 1980s)	• Diversified businesses in steel manufacturing and machine controls o Collaboration with Hyogo Rehabilitation in Kobe, Japan founded by Seishi Sawamura, orthopedist whose father was a user-prosthetist	• Developed the first ever prototype of microprocessor controlled prosthetic knee and obtained three patents (1980s-1992) o Leveraged machine controls/materials capabilities in research partnership with Hyogo Rehab • Conducted clinical trials at Hyogo Rehab Center (1989)	• Licensed technology to Blatchford (Incumbent) (1993) and Nabtesco (Nabco; "diversifying entrant" affiliated with Kobe's keiretsu group) (1990s)
Liberty Mutual (1961)	• One of the biggest worker's compensation insurance policy providers in the US since its founding (1912) • Motivated to help injured policy holders to return to work instead of paying for the long term treatment o Established Liberty Mutual Research Center for Safety/Health to help industrial accident victims (1954)	• Under Melvin Glimcher's leadership, Liberty funded the MIT research to develop prototype of myoelectric prosthetic elbow (later the Boston Elbow) (1961) • Hired MIT researchers (e.g. Amar Bose and Norbert Wiener) to further develop the elbow prototype (1960s) • Hired physicist T.Walley Williamson for commercial development (1973) o Partnered with Harvard Med School and Mass General o Bill Hanson (founder of LTI) joined (1984)	• Sold some of the prosthetic research division to Bill Hanson's LTI (employee spinout) (2001) • Completely shut down the research center (2017)
Samsung (2014)	• Diversified businesses in semiconductors and electronic products o Chose mobility assistive technology as a strategic growth area to address needs of fast-growing aging population	• Samsung Science & Technology Foundation funded research projects on medical robots at universities (2014) o Follow-on internal research and 10+ clinical trials in Korea and US • Invested in mobility assistive technology (2014-) • Invested in Pillo, an AI medical robot startup (2018)	• No value capture in prosthetics industry to date

Table 7c: Historical Analysis of Prosthetic Industry Incumbents Sample

Firm Name	Founder/Firm Knowledge Context	Key Technological Investments and Participation in Knowledge Aggregation (year)	Value Capture Strategies in Prosthetics
Blatchford	• Founded by Chas A. Blatchford (1890) • Specialized in O&P o Major limb provider to the NHS (since 1948) o Created the Modular Assmbly Prosthesis (1970s) o Applied carbon fiber material for aircraft to limb prosthetics (1980s)	• Developed Intelligent Prosthesis and Adaptive Knee by integrating microprocessors (MPC), hydraulics & pneumatics technologies o Licensed technology from Kobe Steel (1993) o Combined pneumatic and hydraulic controls with MPCs ('90s) • Developed Elan microprocessor foot by integrating bionics, hydraulic ankle technology & aerospace carbon materials to "restore propulsion ordinarily provided by ankle muscles" (2010s) • Developed intelligent and adaptive prosthesis by managing tradeoffs between new technologies/functions with existing prosthesis	• Entered market with Intelligent Prosthesis+ and Adaptive Prostheses in 1998 • Launched Elan ankle (2011); Orion knee (2014); the LiNX system (integrating Elan and Orion for above knee amputees) (2015)
Ossur	• Founded by Össur Kristinsson, a prosthetist (1971) • Specialized in O&P o Developed the silicone prosthetic liner called Iceross (1986) o Developed carbon-fiber and hydraulic technology by acquiring Flex-Foot (2000)	• Developed Rheo Knee (late 1990s) integrating bionics and hydraulics o Collaborated with MIT's Herr, and licensed technology from him • Developed Power knee by incorporating artificial intelligence o Partnered and licensed technology from Victhom (2003; 2005) • Developed "smart structures" by integrating electronic, mechanical components for "user-extension" functions o Partnered/purchased powered prosthetic ankle technology from SpringActive (2015; 2019) • Developed mind-controlled prosthetics and neuro-interface o Research Trust Fund with Ottobock in Univ. of Iceland (2016) o Licensed from Alfred E. Mann (2019) • Developed wearable technology/exoskeleton for mobility o Partnered with COMAU (part of Fiat-Chrystler) to invest in IUVO for wearable robot technology (2017) • Extended to bionic upper extremity technology and prosthetic lines o Acquired Touch Bionics (Startup) (2016) • Strengthened mechanic prosthetic product lines and technology • Strengthened sales, marketing, and distribution in prosthetics o Acquired Medi Prosthetics (2016); small prosthetic players (2012), distributors and service providers (2014) o Funded Ossur Running and Mobility Clinics partnered with CAF (Challenged Athletes Foundation) (2012)	• Entered market with the Rheo knee (2005) • Launched the Power knee and the Proprio foot (2006); Symbionic leg (integrating a bionic knee and bionic ankle) (2012); i-Limb and i-Limb Digits of Touch Bionics (2016)

Table 7c (Cont'd)

Firm Name	Founder/Firm Knowledge Context	Key Technological Investments and Participation in Knowledge Aggregation (year)	Value Capture Strategies in Prosthetics
Ottobock	• Founded by Otto Bock (1919) and succession to son-in-law Näder • Specialized in O&P o Jupa knee with a brake mechanism (1949) o Pneumatic hand (1962) o Pyramid design and modular system (1969)	• Early experiments in myoelectric hands o Partnered with Viennatone for expertise in electronics (1967-1977) • Developed C-leg through integration of bionics and hydraulics o Licensed technology/partnered with Kelly James (University of Alberta/Biomech Engineering) (1992-1997) • Developed bionic hand by adding sensors in the fingertips (early 2000s) o Partnered with NHS, clinics (Nottingham City hospital) for test fitting • Developed Michelangelo hand by integrating electrodes and electromyography software o Partnered with Advanced Arm Dynamics for clinical tests (2008) • Enhanced bionic UL line; gripping patterns/finger movement technology o Acquired BeBionics from Steeper; acquired Freedom Innovation (2017) • Developed the Axon-Bus system (fitting interface) by integrating self-contained data transmission system • Participated in DARPA revolutionizing prosthetics (2007) o Partnered with JHU APL for research on tissue engineering for neural interface • Acquired Neurodan (2005) for neurostimulation technology; Licensed neurostimulation technology from Victhom (2005); Acquired Victhom's division (2011) • Developed mind-controlled prosthetics and neuro-interface o Research Trust Fund with Ossur within the University of Iceland (2016) • Developed wearable technology/Eksoskeleton technology o Licensed from Ekso Bionics (UC Berkeley spinoff) (2014); Partnered with Volkswagen for development; Acquired SuitX (Berkeley spinoff) for robotic exoskeletons (2021) • Strengthened carbon fiber composite technology o Acquired Spring Lite (2001); Freedom Innovation (2017) • Developed fitting technology o Acquired BioPortrait (fitting) (1998); Tech Interface Systems (startup) for volume management technology (fitting) (2003); Respecta (fitting and clinical tests) and Pohlig (fitting) (2013)	• Entered market with C-leg, the first bionic prosthetic knee (1997) • Launched Myo (arm) Systems and Dynamic arm (2003); Michelangelo hand (2010); Genium leg (integrating a bionic knee and ankle) (2011) and Kenevo knee (2015); BiOM (of iWalk) and BeBionic Hand (of Steeper) (2017)

Table 7c (Cont'd)

Firm Name	Founder/Firm Knowledge Context	Key Technological Investments and Participation in Knowledge Aggregation (year)	Value Capture Strategies in Prosthetics
Ottobock (cont'd)		o Partnered with UNYQ (startup) for covering (2015) • Enhanced prosthetic sales, marketing, distribution o Acquired VASI for its presence in pediatrics market (2005) • Strengthened prosthetics manufacturing o Acquired Danforth (2002)	
Steeper	• Founded by Hugh Steeper (1921) • Specialized in O&P; Owned Steeper Clinics, through which it distributed devices in the US & UK	• Started a research program on powered UL components (e.g., electric hands, electrodes, battery, and cabling) in the early 1980s • Developed BeBionic hand by integrating bionics, novel materials (e.g. aerospace alloys) and design principles (2014) o Licensed bionic upper limb technology from BeBionic inventor Mark Hunter in 2008 • Acquired the Espire elbow from College Park Industries (2020)	• Entered market with BeBionic hand in 2010 • Sold BeBionics to Ottobock (2017)
Willow Wood	• Founded by William E. Arbogast, an amputee (1907) • Specialized in prosthetic and orthotic manufacturing o SACH foot (1961) o Carbon Copy II Foot (1984)	• Developed robotic knee through design and integration of titanium, thermal alignment, internal electronics and extended power sources (1999) o Collaborated with Sandia National Lab and Chelyabinsk 70 lab • Developed pattern recognition technology for prosthetic arms o Collaborated with University of Michigan, Cleveland University and Coapt (RIC spinoff) • Launched Willow Venture to invest in new technology	• Entered market with Limblogic (an accessory) (2007)