

Preface

The De Vinci Innovation Center (DVIC) is a community of makers that develops technologies within philosophical and critical frameworks to shape our societies' futures. The objective is to implement real-world solutions as well as design projects to enhance public engagement, improve education, and overall provide scientific knowledge. Our researchers contribute actively to top-level international research in multiple fields, including artificial intelligence, human-computer interactions, education, and ecology. We believe that these objectives require a transdisciplinary approach, that bridges the gap between sciences, techniques, sociology, and philosophy. This is performed by collaborating with other scientists and industrial and startup sharing our values, to form strong research partnerships...

The Artificial Lives group, led by Dr. Clement Duhart, aims to develop the next generation of machines and Human-Machine Interfaces. The group members strongly believe that through the combination of Design and Engineering, human-centered technologies can blend into our environments to become invisible, vastly improving daily lives. To achieve this vision, the members contribute to human-computer interactions, cognitive enhancement through new forms of extended intelligence, learning platforms, and cobotic. Our bio-inspired, multidisciplinary approach couples AI and virtual reality with intelligent materials, robotics and the Internet of Things.

For the past two years, De Vinci Innovation Center (DVIC) students following the Creative Technologies curriculum had the opportunity to develop their vision on technology, innovation, and society. This proceeding is a composition of six master's theses, ranging from Machine Learning, Human-Computer-Interaction to Robotics. The authors strongly believe that developing alternative futures requires new types of engineering that take into consideration both the people's needs and the environment. These documents have been written to reflect this vision and refined over several months with an iterative reviewing supervised by the Principal Investigators.

The Authors, the Principal Investigators and the whole DVIC community is proud of releasing this first proceeding. We dedicate this first edition to Pascal Brouaye and Nelly Rouyres, without whom nothing would have been possible.



List of Theses

HAPTICS IN THE SERVICE OF DIY PROSTHESES

1



TRISTAN JOURNAL - has always been interested in medical engineering and innovation. He was interested in improving the human body and in prostheses.

HAPTICS IN THE SERVICE OF DIY PROSTHESES

TRISTAN JOURNAL

Today, technology plays an increasingly important role at the heart of global issues; technological accessibility has become imperative for improving the quality of life for everyone, including individuals with specific needs. This thesis embarks on a thorough exploration of the intersection between haptic technology, prosthetics, and technological accessibility.

The DIY (Do It Yourself) kit is at the heart of this research, offering an innovative approach to empower users to design and customize their prosthetics. By harnessing the capabilities of haptic technology, this kit aims to enhance user experiences by providing precise and intuitive sensory feedback.

Throughout this thesis, we will address several critical dimensions, including prosthetic design, selecting suitable materials, and integrating haptic components to enhance sensory perception. Additionally, we will explore the possibilities bio-materials offer to create bio-patches integrated into prosthetics, thereby opening new horizons in rehabilitation.

This research advocates for a straightforward approach by emphasizing the convergence of technology and accessibility. Furthermore, it paves the way for democratizing medical innovation by enabling users to take charge of their rehabilitation.

Beyond the technical results, this thesis contributes to a reflection on how technology can serve inclusion and improve quality of life, strengthening our understanding of the relationship between humans and machines in the context of modern prosthetics.

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1.1 Context

Over the past few decades, technological innovation has played a crucial role in transforming our societies, influencing every aspect of our daily lives, from communication to healthcare, education, the economy, and much more. As revolutionary new technologies emerge rapidly, access to these innovations has become a significant concern to ensure an inclusive and equitable society.

One of the areas that has seen exponential technological revolution is the field of medicine. Throughout the ages, humans have sought to understand their bodies, improve their daily lives, and increase longevity. The earliest traces of medical practice date back to antiquity, with civilizations such as the Egyptians, Greeks, and Romans. For example, the Edwin Smith Papyrus (Fig 1.1), dating back to around 1600 BC [1], is one of the oldest known medical documents and addresses various medical conditions and procedures. The Renaissance and the Scientific Revolution marked a period of significant medical innovation, with figures like Andreas Vesalius (Fig 1.2), who revolutionized anatomy [2], and Ambroise Paré. The 19th and 20th centuries represent an essential period of medical innovation with the development of vaccination by Louis Pasteur or the advent of modern surgery and medical imaging techniques. Medical innovations continue to emerge and represent a continuous trajectory of evolution.

Among these medical innovations, one of the most significant is the field of prosthetics, which seeks to replace, support, or enhance a lost functionality or severely damaged part of the human body. The emergence of early prosthetics dates back to antiquity, with archaeological discoveries in Egypt revealing the existence of prosthe-

ses dating back over 3,000 years [3]. Examples include artificial toes and fingers made of wood and leather (Fig 1.3). Although rudimentary, they testify to the ingenuity and perseverance of humanity in overcoming challenges related to injuries and amputations. The field has seen significant advancements in recent decades thanks to rapid progress in engineering, biomechanics, robotics, and neurology. These advancements have led to sophisticated prostheses replicating movements and functionalities similar to human limbs.

Numerous prostheses exist today, varying based on their design, components, and functionality. The main categories include:

- Passive Prostheses:** These are primarily aesthetic devices designed to replace a missing part of the body visually.
- Mechanical Prostheses:** Mechanical components, such as joints and cables, are used to restore the functionality of a body part.
- Myoelectric Prostheses:** Controlled by electrical signals generated by the wearer's muscle contractions. Electrodes capture the user's unique and natural movements, reproducing them with simple muscle contractions, enabling more complex and natural movements. They are commonly used for arm and hand prostheses. COAPT has developed a myoelectric control device for upper limb prostheses. This controller is compatible with various prosthetic brands, including Ossür, Psyonic, and Taska. Instead of focusing on the prosthetic design, this company specializes in creating myoelectric control devices [4].
- Hydraulic and Pneumatic Prostheses:** These use fluids (liquids or gases) to create fluid and controlled movements.
- Bionic prostheses:** incorporate advanced electronic components and sensors to replicate movements and functionalities similar to a human limb's. A notable example is PSYONIC [5], which develops bionic prostheses. Using sensors, their prosthesis sends vibrations to the user, allowing them to feel and understand the actions performed with the prosthesis. Furthermore, this prosthesis combines various production methods, such as 3D printing, silicone injection, and CNC machining [6]. This approach makes the prosthesis versatile, high-performing, and durable.

In conjunction with prostheses, two significant domains of technological innovation are emerging: haptic and bio-patches. These elements, integrated into prostheses, represent avenues for exploration.

The earliest references to haptic can be found in ancient texts from ancient Greece and China, where philosophers and physicians began to explore the senses, including the sense of touch. For example, Aristotle wrote about tactile perception in his work "De Anima" (On the Soul). The term "haptic" was introduced in the 20th century to refer to studying the sense of touch. The field of haptic has seen significant development during this century, especially with the emergence of tactile technology and human-machine interfaces. Today, haptic has become a full-fledged interdisciplinary discipline with applications in virtual reality, robotics, medical simulation, and many others [7]. Haptic is ubiquitous in our environment, and we experience it daily without necessarily being aware. A typical example can be found in our smartphones, which go beyond simple vibrations to provide an interactive interface and sensory feedback to users during interactions with applications [8]. This is notably the case with Apple's taptic engines in iPhones. The use of haptic extends to other fields, including the video game industry. Sony has placed great importance on haptic feedback in their PS5 controller to enhance player immersion [9]. Additionally, startups like Acronika are dedicated to developing haptic technology in virtual reality, particularly with their skinetic suit, offering new gaming experiences [10].

In the 1970s, the first work on bio-patches was carried out in medicine, particularly in developing skin patches for controlled drug release. These patches were used to administer drugs continuously and controlled through the skin, such as the patches from Purdue University [11]. Bio-patches designed for the heart are also manufactured using 3D printing technology, an innovation developed by the University of Sydney. After scanning the patient's heart, the team creates a 3D model of the area requiring transplantation and then designs a

specific cardiac patch to cover the damaged area [12]. Today, bio-patches are gaining popularity and diversifying. They are increasingly used for home monitoring, telemedicine, and rehabilitation applications.

1.2 Research Domain

The research topic of this thesis lies in the domain (of wearable technologies) of DIY and prosthesis innovation. Several disciplines - haptic, design and modeling, and bio-materials science - intertwine, making this research topic a multidisciplinary field.

Haptic and the idea of improving prosthesis is at the base of this project. Haptic technology refers to the study and development of technologies that enable a user to receive touch-based feedback through a device. This feedback can be in the form of vibrations, pressure changes, or other physical sensations that simulate touch or provide additional information about the device's actions.

Engineering design and modeling are essential to innovation, combining creativity and precision. The invention extends beyond aesthetics; it involves creating products, systems, and processes that meet requirements effectively, efficiently, and ethically. At the same time, modeling enables us to simulate and analyze complex systems before they are implemented, to predict their behavior, identify potential problems, and optimize performance.

The field of bio-materials is interdisciplinary, drawing on knowledge from materials science, biology, medicine, and engineering. Bio-materials research aims to develop new materials and technologies to improve health outcomes and quality of life for people with various medical conditions. It allows the understanding of the properties of the materials, allowing a better exploitation of them.

1.3 Problem statement

The wide range of demands and technological possibilities for prosthesis development offers many design, improvement, and innovation opportunities. However, the complexity, standards, cost, and rigor required in this field can make technological innovation and accessibility difficult. To meet this challenge, design tools, and methods are needed to simplify prosthesis innovation and enable a first step towards haptic. Indeed, innovation in haptic and prosthetics can present particular difficulties for people unfamiliar with these fields.

1.4 Research approach

The work presented in this thesis attempts to understand the constraints, expectations, and opportunities for innovation in haptics and prosthetics and to provide simple design techniques and methods.

Firstly, It begins with an ethical exploration, seeking to understand today's technological accessibility. And starts a reflection on emerging challenges and possible solutions.

Then, it explores how manufacturing technologies and processes can be used to innovate, their use, and applications. It reviews the state of the art and related works in the various fields covered in this paper, their use cases, and limitations, thus increasing knowledge and experimental possibilities...

Next, a comprehensive approach is taken to the design of various prototypes. Several of these are manufactured and tested. Mechanical evaluations and user tests are carried out to iterate and improve the prototype until a final version that best meets the requirements and challenges identified is achieved.

1.5 Scientific contribution

This thesis makes the following contributions :

Fabrication method

1. Contribute to the DIY design of a low-cost haptic kit for prostheses with different components, design methods, and uses.
2. Contribute to the design of bio-patches with a method accessible to all and bio-degradable materials.

Methodological contribution

1. Contribute to systematically exploring design and prototyping possibilities through different materials and methods for fabricating prostheses or bio-patches.

Empirical contribution

1. Proposing an in-depth study of four low-cost materials for prototyping both bio-sourced, water-based, and biodegradable patches: alginate, gellan, gelatin, and glycerine.
2. Explore how haptic components and prostheses can be combined to create functional interactive devices.
3. Proposes an ethical reflection on technological accessibility at different levels.

1.6 Structure of the Thesis

This thesis revolves around using haptic for prosthetics and its technological accessibility. Chapter 1 is an ethical reflection on technical accessibility at different scales and provides a current overview. Chapter 2 introduces the field of haptic, various related components, and how to use them, offering an overview of haptic-based technologies and research. Chapter 3 focuses on prosthetic and bio-patch design, offering DIY-based solutions. It provides an overview of different prosthetics and the implementation of haptic in them and describes previous

work on bio-materials and bio-patches. Finally, this thesis concludes the work and summarizes the discoveries and contributions.

2.1 Introduction

Over the past decades, technological innovation has played a crucial role in transforming our societies, influencing nearly every aspect of our daily lives, from communications to healthcare, education, the economy, and much more. As new technologies emerge rapidly, access to these innovations has become a significant concern to ensure an inclusive and equitable society.

Accessibility to innovation refers to the ability of all individuals, regardless of their social background, economic situation, place of residence, or physical condition, to benefit from and contribute to technological and scientific advancements.

Medical innovation has improved millions of people's health and quality of life worldwide. Revolutionary advances in healthcare, research, and technology have made diagnosing, treating, and preventing many previously considered incurable diseases possible. However, equitable access to these medical innovations remains a significant challenge for many populations, especially those in disadvantaged or marginalized regions.

Accessibility to medical innovation, therefore, refers to the capacity of individuals, communities, and countries to benefit from the latest medical advancements and derive tangible health benefits from them. This includes access to new treatments, medications, medical devices, and cutting-edge technologies in the healthcare field.

Unfortunately, many regions face significant challenges regarding access to medical innovation. Economic, social, and geographical disparities can lead to limited access to healthcare and innovative treatments. In developing countries, access to adequate healthcare infrastructure

and advanced medical resources can be a significant hurdle for many individuals, especially in rural areas.

Furthermore, the high cost of innovative medical treatments and technologies can render these options unaffordable for many individuals, even in developed countries. This accentuates health inequalities and leaves vulnerable populations without access to the best medical solutions.

The challenge of accessibility to medical innovation requires a comprehensive and collaborative approach. Governments, international organizations, pharmaceutical companies, and healthcare stakeholders must work together to develop policies and strategies to remove financial, geographical, and structural barriers that hinder access to medical innovations.

2.2 Related Work

Accessibility to technological innovation aims to make technologies accessible to all individuals, regardless of their abilities or specific needs. This approach is based on the fundamental principle that advancements should be designed inclusively, allowing everyone to benefit from their opportunities. Here is an overview of the main aspects of accessibility to technological innovation:

Digital accessibility involves designing websites, mobile applications, software, and online content to be usable by all individuals, including those with visual, auditory, motor, or cognitive impairments. Researcher Shari Tewin has been involved in numerous projects based on assistive technologies, such as screen readers for blind people, adapted keyboards, eye-tracking interfaces, assistive communication devices, and more [13][14][15][16]. Assistive technologies are devices and software designed to help individuals with specific needs use technology more effectively, improving digital accessibility.

The Internet of Things (IoT) refers to the process of connecting physical objects to the Internet. It opens up new

opportunities for technological innovation, but it is essential to ensure that these connected devices are accessible to all users. This requires inclusive design and consideration of various needs. IoT is particularly relevant in the medical field with electronic health records, offering more precise, reliable, and accessible patient data. However, it can also pose privacy risks if misused [17]. IoT is increasingly present in connected greenhouses[18] and smart farming[19][20] areas, providing valuable support to farmers in monitoring and improving their product management.

Accessibility to technological innovation must also include ethical considerations for using artificial intelligence (AI), which is increasingly significant in modern technologies. It is essential to ensure that AI does not perpetuate existing biases or discrimination. AI solutions play a growing role in decision-making and interactions, potentially impacting positively and negatively. Considering the needs of users with disabilities can help technologists identify high-impact challenges whose solutions can advance AI for all users[21].

In some countries, laws and regulations have been implemented to promote accessibility to technological innovation. For example, the Americans with Disabilities Act (ADA) in the United States requires businesses and organizations to provide accessible services to people with disabilities, including online services. Medical technological innovation often involves collecting and analyzing large amounts of health data. Accessibility to these technologies must be balanced with significant ethical considerations regarding the protection of patient privacy and data confidentiality. Stringent security measures must be implemented to ensure that sensitive medical information is protected and used ethically[22]. In some cases, like in China, measures have been implemented to track and restrict the movements of its citizens during the COVID-19 pandemic, raising ethical concerns[23].

In conclusion, accessibility to technological innovation is an ever-evolving field that aims to ensure that technolog-

ical advancements benefit everyone without exclusion. It's an essential approach to building a more inclusive and equitable world where everyone can enjoy the opportunities and benefits of the ongoing technological revolution. The commitment of designers, policymakers, and society is necessary to continue progressing toward full accessibility in technological innovation.

2.3 Ethics of Accessibility

2.3.1 Accessibility to Technological Innovation

Ethics in technological accessibility is a crucial consideration in our modern society. As technology continues to advance rapidly, it is imperative to ensure that the benefits of this progress are accessible to all individuals, regardless of their specific needs or abilities. Technological accessibility encompasses the provision of hardware devices and the design and development of software and applications that allow everyone to access information and digital services equitably and inclusively.

As a society, we are responsible for ensuring that no one is left behind in this ever-expanding digital era. As Tim Berners-Lee, the creator of the World Wide Web, emphasizes, "The power of the Web is in its universality. Access by everyone, regardless of disability, is an essential aspect." [24].

Technological ethics also require recognizing the diversity of user needs. Each individual has different abilities and limitations, and it's essential to design technological solutions that account for this variability.

This accessibility is based on the principles of equity and inclusion, ensuring that all individuals, regardless of constraints, can benefit from technology's opportunities. As Vint Cerf, one of the pioneers of the Internet, reminds us: "An accessible Internet is an Internet for all."

Technology designers and developers must incorporate

accessibility from the outset of the design process, as emphasized by Steve Ballmer, former CEO of Microsoft: "Accessibility is not a feature; it's a responsibility." This approach helps identify and address accessibility issues before they become obstacles for users. By focusing on accessibility, we acknowledge that every person has the right to access information, education, employment, and other essential services equitably. The ultimate goal of technological accessibility ethics is to build an inclusive world where everyone can fully participate and benefit from the ongoing technological revolution.

Technological accessibility extends beyond people with disabilities to individuals with specific needs based on age, culture, language, or socio-economic status. As highlighted by the United Nations in its report "Digital Inclusion for All: Empowering the Poor and Vulnerable" [13], technological accessibility plays a crucial role in reducing inequalities and empowering marginalized populations.

To achieve true technological accessibility, promoting collaboration is essential. Researchers have emphasized the importance of collaboration among designers, developers, users, and disability rights advocacy groups to ensure an inclusive, user-centered design. Active user participation throughout the development process is essential for identifying accessibility issues and finding suitable solutions, as noted by Shari Trewin in several articles [25][16].

Privacy protection and data security are also important aspects of technological accessibility ethics. As advanced technologies collect and analyze increasing amounts of data, it's crucial to ensure that this information is used ethically and does not infringe on individuals' fundamental rights. Vital regulatory and ethical frameworks must be established to protect individuals' privacy while promoting innovation.

In conclusion, technological accessibility and its ethics are matters of social justice and respect for the fundamental rights of every individual. By ensuring technology's

accessibility to all, we work towards a world where everyone can fully participate, contribute, and prosper. As Albert Einstein said: "The value of a man is in his ability to give and not in his ability to receive." However, this challenge is compounded by the issue of accessibility to medical innovation, which represents a significant and growing part of innovation.

2.3.2 Accessibility to Medical Innovation

The ethics of medical innovation accessibility is a fundamental topic sparking many debates in healthcare. As technological advancements continue transforming medicine and opening up new prospects for health, it's crucial to ensure that these developments benefit the entire population, regardless of their socio-economic status or residence. This graphic representation highlights disparities in accessibility to prostheses in South Africa linked to origins, underscoring the challenges to be addressed [26].

According to an article published in "The Lancet" in 2018, "access to medical innovations remains unequal world-wide, with significant disparities between low-income and high-income countries" [27]. These disparities can be attributed to the high cost of advanced medical treatments and technologies, geographical and logistical barriers, and inadequate healthcare resources and infrastructure. For instance, Mali aimed to make healthcare accessible to all at its independence in 1960, but poverty and resource shortages prevented it from achieving its goals [28].

Medical innovation can offer disease diagnosis, treatment, and prevention solutions. However, these advancements can also be expensive, raising ethical questions about fairness and justice in access to healthcare. As the World Health Organization (WHO) reminds us: "The right to health includes access to essential healthcare services, medicines, and medical technologies for all, without discrimination." He estimates that 650 million people worldwide are disabled. This equates to approxi-

mately 10 percent of the world's population. Of those people, 80 percent live in low-income countries [29][30]. It's also estimated that while 35–40 million people currently require prosthetic or orthotic services, only 1 in 10 persons has access to such services [26]. Ethics of medical innovation accessibility demand a balance between promoting innovation and ensuring its benefits are not reserved for a privileged elite. Health policies and financing mechanisms must be in place to make these new technologies accessible to all individuals in developed or developing countries, whether they live in urban or rural areas. Several countries, like France, have started on this objective using calculation methods and analysis to ensure equitable distribution and accessibility throughout the territory [31].

One notable issue is related to patents. Unlike pharmaceutical manufacturers, many commentators argue that patents stifle biomedical research, for example, by preventing researchers from accessing patented materials or methods needed for their studies. Patents have also been accused of hindering medical care by increasing drug prices in poor countries [32]. The article's authors emphasized the need for policy and social initiatives to promote a more equitable distribution of medical advancements to improve global health as a whole.

Another critical dimension of medical accessibility ethics concerns equitable participation in clinical trials and research. A study by Yaqi Yuan at Wake Forest University, USA, found that in 30 countries, only 17 percent of people were satisfied with their healthcare facilities [33]. New therapies and medical technologies must be rigorously and ethically tested, and it is essential to include diverse and representative populations in these studies. This ensures that the results apply to various populations and that the benefits of innovation are distributed equitably. As some researchers highlight:

"Inclusive and diversified medical research is essential to ensure therapies and treatments are suitable for all patients."

Digital technologies and mobile health applications offer considerable potential to improve medical innovation accessibility. A research report from the World Health Organization (WHO) in 2019 stated that "digital health technologies can play a key role in improving access to healthcare in remote areas and low-income countries" [34]. This can include solutions such as telemedicine, chronic disease tracking apps, and health education tools. However, this raises ethical concerns about data privacy and health data protection. With the advent of information and communication technologies in healthcare, it is essential to ensure the security and privacy of patient medical information. As American cardiologist and researcher Eric Topol pointed out:

"Future medical technologies can only succeed if they preserve patient privacy."

This implies establishing strict data protection standards and ensuring that access to medical information is restricted to authorized healthcare professionals.

The COVID-19 pandemic has exposed weaknesses in global healthcare, highlighting challenges in international coordination, information exchange, and healthcare accessibility. Healthcare systems have suffered from a lack of preparedness and coordination, exacerbated by disparities in medical resources. The rapid exchange of medical information has proven crucial, underscoring the need for a global platform to facilitate this communication. Furthermore, unequal access to healthcare has heightened the urgency of making medical innovations accessible to everyone, regardless of their resources [35].

In conclusion, the ethics of medical innovation accessibility is a significant concern in our quest to improve healthcare and address current and future medical challenges. By focusing on equity, inclusion, and the protection of patient rights, we can ensure that the benefits of medical advancements are extended to all, regardless of socio-economic or geographical context. Society and policymakers are responsible for ensuring that medical

innovation is accessible to all, thus contributing to a more ethical, sustainable, and well-being-centered healthcare system. Many areas touch upon medical innovation accessibility. Although not well-known to the general public, the field of prosthetics represents a significant issue with unique complexities.

2.3.3 Accessibility to The Prosthetics Field

The ethics of prosthetic accessibility is a crucial issue that raises significant ethical and social considerations. Prosthetics are vital in improving the quality of life for amputees and individuals with physical disabilities, allowing them to regain lost mobility and independence. However, accessibility to these technologies raises questions about equity, costs, quality, and patient rights.

Prosthetic accessibility primarily involves two aspects: physical access and financial access. Physical access refers to the availability of prosthetics tailored to the specific needs of individuals, while financial access pertains to people's ability to afford prosthetics at a reasonable cost. In low-income or middle-income countries, limited prosthetic access can be due to financial constraints and limited healthcare services. This is the case in Sierra Leone, where access is minimal, with limited staff, leading to amputees being isolated from the population. This gap is exacerbated between rural and urban areas [36].

In the USA, annual prosthetic service caps in private health care plans typically range from \$500 to \$3000 in annual coverage. Lifetime restrictions have an even greater range, with some insurance plans covering up to \$10,000 and others only a single device during an amputee's lifetime [37]. These caps limit access to prostheses, particularly to high-tech devices, which are considerably more expensive, showing inequality even within countries with higher access [38]. A high budget does not guarantee quality; for instance, countries like the USA spend several billion dollars on their healthcare system but face issues with quality and price. In contrast, countries like

Costa Rica, Thailand, and Singapore spend an average amount but provide high-quality healthcare. Thus, it is crucial to focus on quality and healthcare accessibility for countries [39].

The United Nations Convention on the Rights of Persons with Disabilities emphasizes the importance of ensuring access to assistive technologies, including prosthetics, for disabled individuals:

"States Parties commit to ensuring and promoting the effective access of persons with disabilities to new technologies and information and communication systems, including the Internet." Notably, countries like France and international organizations like the WHO are working to promote innovation and make it accessible to all through action plans or agreements [31][29][40][41].

Many organizations, including nonprofits and hospitals, are attempting to improve accessibility to prosthetic devices. Despite the attempts of these various organizations, 95 percent of the amputee population in developing countries still lacks access to proper prosthetic care and affordable devices. Prosthetic accessibility extends beyond providing physical devices and encompasses access to specialized medical care, training for their use, and ongoing support to meet individual needs. In Kenya, the Orthopedic Technology Department of the National Hospital employs an average of 18 people to serve around 280 patients each month. The annual budget of this hospital is \$8,000 [42], highlighting the limits of medical innovation accessibility in poor countries.

Within the framework of the ethics of prosthetic accessibility, it is crucial to ensure that these technologies are available to everyone, regardless of their ability to pay. Efforts must be made to make prosthetics affordable and accessible to people from all walks of life. The World Health Organization estimates that, in the developing world, there are 40 million amputees, and only 5 percent of them have access to any form of prosthetic care [43]. Research conducted by Gulrez [44] underscores the importance of user-centered design in prosthetic

development. These studies emphasize that considering users' needs and preferences is essential for improving the acceptance and effectiveness of prosthetics.

Access to advanced technologies is another aspect of the ethics of prosthetic accessibility. While new technological advancements continuously enhance prosthetics, it's essential to ensure that these technologies are not only available to a privileged elite but benefit all those in need. Finally, the confidentiality and security of user data with prosthetics must be considered. As mentioned earlier in the section on medical innovation accessibility, it's essential to ensure that the sensitive medical data of prosthetic users is protected and that its use complies with ethical and legal standards.

In conclusion, the ethics of prosthetic accessibility is a complex issue that requires deep reflection on equity, financial access, user-centered design, and data security. By ensuring fair and affordable access to prosthetics, developing them with user needs, and protecting their privacy, we can improve the lives of millions worldwide and promote a more inclusive and equitable society.

2.4 Project impact

This project represents an initiative aimed at promoting accessibility and innovation in the field of prosthetics by integrating the principles of haptic and 3D manufacturing. The goal of this work is to restore sensations in amputated individuals by creating a kit designed for forearm prosthetics. It opens the way for a thought process based on accessibility to innovation, particularly in the still relatively unexplored areas of haptic and prosthetics. While these areas remain unfamiliar to the general public, this project serves as a first step to raise awareness and expand access to these technologies.

Prosthetics

Accessibility to prosthetics has profound societal implications. While some are privileged to access sophisticated

and custom prosthetics, many face financial and geographical barriers. As a result, progressive initiatives are emerging to rebalance this disparity by providing accessible and functional prosthetics. This project presents a simplified initial approach to acquiring a device to enhance prosthetics. It allows individuals to actively engage in rehabilitation by involving them in the design and improvement process. The project aims to remain simple while providing all the necessary resources to enable as many people as possible to adopt this approach. Currently, modeling software is limited to a minority of the population, as is the knowledge of 3D printing materials and their use in prosthetics. The goal is to ensure that every amputated individual, regardless of background, can benefit from prosthetics that improve their quality of life, mobility, and well-being.

Haptic

Although it represents a crucial technological advancement, Haptic remains a relatively unknown field to the general public. Electronic devices open the door to rich sensory experiences, but technical and financial barriers limit their adoption. Efforts are being made today to democratize access to haptic. This includes the design of affordable devices, creating user-friendly software, and raising awareness of the possibilities offered by this technology. Accessibility to haptic significantly impacts various fields, such as medicine and virtual reality. This project takes an approach that allows individuals with no prior experience in haptic to use this technology to improve their prosthetics, among other applications. It assists users in their initial steps into haptic while remaining simple and accessible to all. By introducing the field and its various components and suggesting various possible uses, the project represents an affordable and easily accessible technological advancement. However, its primary goal remains the improvement of prosthetics.

This project, though preliminary, illustrates the intersection of technological innovation and social accessibility. By providing an affordable and user-friendly kit, offering

components and code accessible to all, and 3D prosthetic prototypes, this initiative aims to strengthen the ethics of technological accessibility. The combination of haptic and prosthetic concepts makes this approach innovative and potentially replicable on a larger scale.

In the end, this project represents a first step toward inclusive technological accessibility. By integrating technological advances accessible to all, it addresses inequalities in access to innovation. By combining haptic innovation with prosthetic design, this project is based on a thought model centered on accessibility to innovation, which is now a crucial step for the future of our society, thus improving the lives of individuals and contributing to the transformation of a more equitable society.

2.5 Conclusion

The accessibility of technological and medical innovation represents a significant challenge of the 21st century, transcending economic, societal, and political borders. This issue embodies an unprecedented opportunity to steer society toward more significant equity, progress, and inclusion. At the intersection of political, economic, and societal issues, equitable access to technological and medical advancements drives global impact and transformation.

From a political and economic standpoint, innovation is central to global competitiveness. Nations that prioritize innovation as a strategic cornerstone shape the international landscape by generating innovative ideas and influencing global standards. This dynamic brings global recognition to countries and bestows a robust and influential voice in global negotiations. Enhanced accessibility to innovation enables a country to engage in international trade and contribute to global exchanges.

From a societal perspective, universal accessibility to innovation fosters regional and national attractiveness. Regions open to innovation become incubators of economic growth and social well-being. By creating an

environment conducive to innovation, these areas attract talent, stimulate foreign investments, and infuse creative energy. Consequently, accessibility to technological and medical innovation serves as an engine for development, reinforcing social cohesion and the global appeal of nations.

Key stakeholders, whether governments, international organizations, or businesses, play a pivotal role in ensuring accessibility to innovation. They are responsible for designing and implementing policies and initiatives that balance technological development and social inclusion. However, the impact of local initiatives and smaller-scale actors should not be underestimated. These initiatives have the power to catalyze research and initiate significant changes on a small scale, often leading to far-reaching repercussions beyond their original scope.

In summary, accessibility to technological and medical innovation is an opportunity to reevaluate the foundations of our contemporary societies. Political, economic, and societal considerations underscore the imperative to open the doors of innovation to all, without distinction, by promoting equity and inclusion. Whether through global or local initiatives, accessibility to innovation offers a future where technological progress knows no bounds, and each individual can contribute to collective flourishing.

First Step into the Field of Haptic

3

3.1 Introduction

The field of Haptic has emerged as a central area of research and innovation in a constantly evolving technological landscape. While human-machine interaction is at the heart of technological development, the sense of touch has often been overlooked. In contrast, significant attention has been given to enhancing visual and auditory interfaces, neglecting the tactile modality. Derived from the Greek "haptikos," meaning "capable of touching or grasping," haptic is the study of tactile perception and the simulation of touch through technology. This multidisciplinary field combines engineering, psychology, neuroscience, and human-computer interaction elements to create experiences that engage our sense of touch, thereby enriching how we interact with the environment and digital devices.

Touch is an integral part of human perception and communication, crucial in conveying emotions, texture, and spatial information. This is the case for blind individuals who primarily rely on their senses of hearing and touch to understand the world. They use touch to discern objects, navigate, or even read using Braille language [2]. Furthermore, technological innovations based on the sense of touch and haptic are being developed to assist blind individuals [3][4]. It enables us to comprehend the world around us and interact with it.

Aware of this, researchers and engineers strive to harness haptic to bridge the gap between the physical and digital realms. The growing interest in haptic stems from the desire to create more immersive technological experiences. Traditional interfaces, which rely heavily on visual and auditory senses, often fail to convey depth, material properties, or the feeling of presence that physical interactions offer. Haptic technology can revolutionize

how we interact with devices, applications, and virtual environments, as well as provide an alternative mode of interaction for individuals with visual or auditory impairments. Furthermore, as technology extends into areas such as virtual reality and augmented reality and plays a significant role in medicine [5], haptic becomes even more crucial in enabling realistic and impactful experiences.

One of the earliest applications of haptic technology was in early 20th-century light aircraft lacking servo mechanisms. When the aircraft approached a stall, the pilot would feel aerodynamic vibrations through the controls. This served as a valuable warning of dangerous flight conditions [6][7].

The first force feedback game controllers were commercialized in the 1990s, introducing haptic motors into video game controllers, such as with the Nintendo 64 in 1997. These controllers let players feel vibrations corresponding to in-game events, enhancing the gaming experience. The Oculus Rift virtual reality headset, launched in 2013, marked a significant milestone in integrating haptic technology into virtual reality experiences. It revitalized interest in haptic in the video gaming domain [9][10]. It was followed by other virtual reality devices with improved haptic capabilities, such as the HaptX haptic gloves [11].

The 2000s saw the emergence of the first mobile phones equipped with haptic feedback. For example, the Nokia 5800 XpressMusic (2008) provided tactile feedback when using the touchscreen [12]. This was just the initial step in mobile haptic, as it did not allow users to customize the haptic feedback. Currently, haptic feedback is integrated into all our phones, with Apple's Taptic Engine being one of the most prominent [13].

This work aims to make haptic more accessible to the general public to enhance human-machine interaction and add a new dimension of interaction to technologies like prosthetics, for example. Through a series of experiments, the development of DIY kit prototypes, and user

testing, it explores the principles of tactile perception, design, components, and the implementation of effective haptic interfaces, along with their impact on the user experience. Finally, several possible applications are presented.

3.2 Related Work

Today, the field of haptic takes many forms, characterized by numerous advances and ongoing projects. It encompasses various aspects, whether it pertains to specific types of haptic, particular sensors, etc.

Some of these projects aim to convey specific effects or forces through haptic, employing various means to achieve this.

The PseudoBend project, developed by Seongkook Heo et al. [15], leverages haptic to create the illusion that a rigid device is being stretched, bent, or twisted. Using haptic motors, the vibrations generated during the deformation of an object are replicated and transmitted to the user. Another possibility for haptic transmission is using sound, as demonstrated by the projects of Donald Degraen et al. [16], who designed vibrotactile feedback in a virtual environment using voice. By swinging a lightsaber in virtual reality (VR), haptic feedback can be felt. Furthermore, Evan Pezent et al.'s project [17] offers a method of controlling vibrotactors based on digital audio interfaces. For all these projects, we refer to them as "vibrotactile feedback." This type of haptic feedback communicates with the user using vibrations to simulate various sensations on the skin.

Some projects focus more on haptic interaction and the human body. The project by Paul Strohmeier and his team [18] aims to improve the design and placement of physical interfaces on the body. They use preprocessed kinesiology tape as touch, pressure, and stretch sensors to determine the most suitable body areas for project designs. TactJam, developed by Dennis Wittchen and his team [19], follows a similar approach.

Other projects focus on sensor development and the types of haptics used.

Piezoelectric sensors are prevalent in many projects and are constantly being improved. For instance, the development of a thick-film piezoelectric sensor for the fingertips of prostheses, carried out by Darryl P. J. Cotton and his team [20], allows users to determine the stability of an object without needing a visual assessment, thus boosting their confidence not to apply excessive force. Mingrino et al. [21] studied a method to detect the onset of slipping of a grasped object. The force sensor used included four thick-film piezoresistive force sensors printed on a polymer film, enabling control of normal and tangential forces and determining the friction coefficient threshold for detecting object slippage. Furthermore, N. Muridan and his team [22] demonstrated that small surface features of an object can be detected using piezoelectric sensors integrated into the fingertips of a prosthesis. On the other hand, cutaneous haptic devices at the fingertips can provide cost-effective and portable solutions. However, they may have limitations regarding credible haptic sensations due to the lack of kinesthetic feedback [23].

Finally, projects related to particular domains are developed to address their needs or improve their processes. A concrete example is the field of virtual reality (VR), which is witnessing significant haptic development [24]. When associated with medicine, it can significantly enhance the efficiency of healthcare. For instance, surgeons can train for complex surgeries in virtual environments with realistic haptic feedback. This force feedback directly impacts the user's muscles, and numerous studies have emphasized the importance of combining haptic in surgery and simulator-based training with haptic feedback [25-30].

On the other hand, patients can benefit from rehabilitation through haptic-based exercises, including engaging projects like that of Mark Sivak and his team [31], which offer a hand rehabilitation system integrating interactive games providing haptic feedback to the user. Further-

more, haptic projects specially designed for amputees contribute to their rehabilitation and social reintegration [32]. Finally, the use of haptic for therapeutic purposes is also an avenue being explored [33].

Despite the wide range of applications and processes, all these techniques remain complex for inexperienced users. They either require the use of expensive hardware, the modification and design of machinery, or extensive knowledge in other fields, such as electronics. The project presented in this chapter does not require advanced electronics or programming knowledge, uses simple and affordable components, and allows for an autonomous prototype.

3.3 Concept

The idea of this chapter is simple: to provide a kit of haptic components for designing various haptic enhancements for prosthetics. Sensors are positioned at the fingertips of a prosthetic device. When the user performs actions, these sensors record data such as applied pressure, object shape, or textures. This data is then processed using various micro-controllers, such as the DRV2605 or Teensy. Subsequently, it is transmitted to a haptic motor that vibrates based on the received information. This haptic motor is in direct contact with the user, allowing them to perceive and receive real-time tactile feedback corresponding to their action.

3.4 Evaluation

The device has been tested with various sensors for different applications. A typical pattern repeats:

3.4.1 Setup

A sensor is used and placed at the user's fingertip. It is connected to a micro-controller, in this case, a Teensy. The Teensy is linked to the DRV2605 haptic controller,

which controls the haptic motors. The LRA or ERM motors must be in contact with the user's skin. Choosing a relatively sensitive skin area is preferable to perceiving the vibrations better.

3.4.2 Protocol

Connect the Teensy to a power source. Launch the code corresponding to the sensor used. The software allows real-time visualization of the recorded data, which helps the user better understand the differences between the vibrations they should feel during the test.

Simple Piezo Sensor To measure the pressure exerted by the user with their fingers. Perform various object manipulations, handling them gently or applying more force, pushing lift different objects. Regarding texture, slide the Piezo sensor on other surfaces; it will generate additional data based on surface variations.

Flexible Piezo Sensor To evaluate the surface of objects and the user's environment. Slide your fingers along surfaces; as soon as they come into contact, the Piezo sensor bends and records data transmitted to the rest of the device.

Sound Sensor Place the sensor at the tip of your fingers and run them over different textures and surfaces. The sound your fingers produce on the material is recorded and transmitted to the controller.

The sensor can be considered functional if the variations in vibrations correspond to the different actions of the user and the displayed data. Currently, the sensors that have shown the most efficiency are the Flexible Piezo types.

3.5 Limitations

It's essential to note that this chapter serves as an introduction and may not necessarily represent a significant contribution for individuals with advanced expertise in

this field. It aims to remain accessible to a broad audience, whether in innovation and technology, design and engineering, or even economic aspects. That's why it delves deeply into haptic to ensure clear understanding while keeping it simple.

Hardware

Currently, the prototype uses only one sensor connected to the micro-controller. The next phase, which involves placing a sensor on each finger of the prosthesis, could pose constraints in power, data reading capacity, and data output. The DRV2605 haptic motor driver controls only one ERM or LRA at a time. The overall size of the components can be excessive, limiting its use for certain prostheses and users. Additionally, the motors used are currently too bulky. The haptic effect becomes much less interesting by reducing the mass and increasing the frequency.

software

The current code continuously reads data in real time, which keeps it in constant operation. The accumulation of data and some noise can slow down the entire system.

3.6 Future Works

Innovation in Haptic is still relatively new and represents a path for improvement in engineering. As mentioned earlier, the work presented in this chapter marks a first step and opens the way for numerous potential enhancements.

From a hardware perspective, one improvement for this project is creating a printed circuit board (PCB) to reduce the space occupied by all the components. This is crucial to ensure the efficient use of prosthetics, ensuring that the entire setup is optimal in terms of distance without causing interference or adding extra constraints to the user. Given the rapid evolution in Haptic, it's also essential to stay updated on new components to determine if

they might be better suited and more efficient for this project. Using a controller capable of driving multiple DRV2605 devices is worth considering.

There are opportunities to enhance the project on the software front by integrating new features related to the components into the code. By optimizing the code for faster and more efficient operation, it becomes possible to improve the precision of vibrations. Other features associated with the controllers can be explored to optimize the code and offer new functionalities.

3.7 Conclusion

This chapter represents a first step towards understanding and accessing haptic technology. It explores various types of components, their functionalities, and different ways to use them. Furthermore, it offers multiple practical applications and explicit code that everyone can use. It aims to remain simple and accessible to all. The next chapter delves into prosthetics and presents different prototypes for integrating the haptic components introduced in this chapter.

First Step into the Field of Haptic

4

4.1 Introduction

4.2 Related Work

4.3 Prosthetics DIY

4.4 Bio-Patches

4.4.1 Concept

The goal of this chapter is simple: to provide a simple process for creating bio-patches. By exploring various materials and manufacturing techniques, this section offers a practical DIY guide for bio-patch fabrication. Each patch will consist of two distinct layers. The lower layer will directly contact the skin, while an upper layer will cover it. A haptic motor will be inserted between these two layers to prevent direct contact with the skin.

4.4.2 Constraints

The production of these bio-patches has presented several constraints:

Firstly, there are mechanical constraints. These patches must withstand various mechanical forces such as pressure, stretching, and torsion. They must not tear, remain adequately flexible, and be capable of stretching to follow the movements once applied to the individual's arm. Tear resistance is a mechanical property that measures a material's ability to resist the propagation of cracks. There is no single mathematical formula to calculate this resistance because it depends on various factors, including the sample's geometry, loading conditions, the material's properties, and more.

Next, there are constraints related to attaching the patch to the individual's arm. The part in contact with the skin must be adhesive enough to stay in place, while the outer layer must resist the friction caused by clothing. Friction is the force that opposes motion when one object's surface comes into contact with another. Its magnitude depends on the size of the contacting covers, textures, the forces involved, as well as the angle and position of the object.

Finally, there are constraints related to manufacturing and accessibility. We seek a patch that is durable, easy to produce, made from safe materials, accessible, and cost-effective for users.

Faced with all these constraints, we have carefully examined the choice of materials and developed different bio-patch recipes that could meet most of these requirements.

4.4.3 Materials Used

The choice of materials is of great importance in the design of bio-patches. Faced with our various constraints, we have compiled a list of bio-materials commonly used in the market to select the most suitable ones.

As a result, we have carefully examined the choice of the following materials:

Alginate

It's a natural polysaccharide mainly extracted from certain species of brown algae. It's a biomaterial used in various fields, including regenerative medicine, food product manufacturing, and the pharmaceutical industry. Alginate is valued for its bio-compatibility, ease of use, and ability to form gels.

Mechanical Strength: Alginate in gel form generally possesses moderate mechanical strength. The strength will depend on the solution's alginate concentration and the gel's quality formed. The higher the alginate concentration, the stronger the gel typically is.

Flexibility and Elasticity: Alginate gels are often flexible and can be stretched without breaking. This makes them a popular choice for applications involving flexible or stretchable materials.

Deformation: Alginate gels can be deformed under stress, making them suitable for applications where some deformation is desired, such as scaffolds for cell culture or flexible medical dressings.

Viscosity: Alginate solutions are often viscous, facilitating their handling and use in manufacturing processes such as 3D printing.

Glycerin

Or glycerol, is a thick, colorless liquid belonging to the alcohol family. It is soluble in water and exhibits high viscosity. Due to its versatile chemical and physical properties, Glycerin has wide applications in various industries, including the food, pharmaceutical, cosmetic, and chemical industries.

High Viscosity: Glycerin has a relatively high viscosity, making it thick and sticky. This property makes it valuable as a thickening agent.

Lubricant: Due to its viscosity, glycerin is often used as a lubricant. It can reduce friction between moving surfaces, making it a common ingredient in industrial and personal lubricants.

Hygroscopic: Glycerin can absorb moisture from the air. This makes it an effective moisturizing agent in cosmetics and skin creams, as it can help maintain skin hydration and absorb sweat.

Chemical Stability: Glycerin is chemically stable, making it useful as a solvent in various chemical applications.

Gelatin

It's an animal-derived substance from the collagen found in animal tissues, typically bones and skin. It is widely used in the food, pharmaceutical, cosmetics, and other

industries due to its gelling and thickening properties.

Gelling: The most well-known property of gelatin is its ability to form solid gels when cooled after being heated in a solution.

Mechanical Strength: Gelatin gels typically have mild mechanical strength. This means they can maintain their shape and structure but be relatively soft and delicate.

Limited Elasticity: Gelatin gels lack elasticity compared to other gelling materials. This means they cannot be stretched or deformed significantly without breaking.

Gellan

It's a natural polysaccharide produced by bacteria of the genus *Sphingomonas*, used as a gelling and thickening agent in the food industry and other applications. It is appreciated for its ability to form gels of varying consistency and stabilize suspensions, making it a versatile ingredient.

Gelling: The most notable property of gellan is its ability to form gels under the influence of cations such as calcium or magnesium. Depending on ion concentration and gelation conditions, gellan gelation can range from flexible to rigid.

Compatibility with Other Ingredients: Gellan can mix effectively with other ingredients, making it an excellent stabilizer for suspensions and emulsions. It can enhance the texture and stability of various products.

Heat Resistance: Gellan gels can withstand relatively high temperatures without breaking down.

pH Stability: Gellan gels generally remain stable over a wide pH range.

Due to their versatility, compatibility with other materials, ease of manufacturing, and affordable cost, we have chosen to use these materials in the design of our

bio-patches. It's essential to note that the mechanical properties of these materials can vary depending on parameters such as concentration and gelation conditions. By experimenting with different combinations, we can obtain bio-materials with diverse properties.

4.4.4 Fabrication Process

Bio-Materials

Bio-Patches

4.5 Evaluation

Prostheses

Bio-Patches

4.6 Limitations

It's important to note that this chapter serves as an introduction and may not necessarily contribute significantly to individuals with advanced expertise in these fields. Its goal is to remain accessible to a broad audience, whether in innovation and technology, design and engineering, or even economic aspects. Therefore, it delves into depth to ensure clear understanding while keeping things simple.

The prosthetics and design approaches described are preliminary prototypes. They are specifically designed for arm prosthetics and may have limitations depending on the individual's type of amputation. Access to 3D printing and materials can also be a constraint for some individuals.

The bio-materials, patches, and various design methods outlined in this chapter have certain limitations. Despite user-friendliness and affordability, they represent initial attempts and are not designed for long-term

durability. They tend to detach and degrade quickly, requiring frequent replacements. Additionally, for optimal effectiveness, it's recommended to have the necessary equipment, including a thermal mixer, which may not be accessible to everyone. Currently, considering the use of commercially available patches is advisable.

4.7 Future Works

It is essential to emphasize that these fields are vast and promising for innovation. They will continue to evolve in the decades, offering numerous opportunities. As mentioned earlier, the work presented in this chapter represents a first step and paves the way for many potential improvements.

There is room for improvement in prosthetics by offering multiple prosthetic models better suited to different types of amputations. This involves enhancing and rethinking design approaches to make them more accessible and considering the use of new materials.

Regarding bio-patches, it is intriguing to explore the development of new bio-patches with a stronger focus on medical models, even though this requires more advanced knowledge and skills, along with higher costs. Additionally, contemplating using new materials such as kombucha presents an opportunity for improvement.

4.8 Conclusion

This chapter represents the first step towards creating a DIY kit to enhance prosthetics. It provides essential knowledge in the fields of prosthetics and bio-patches. Through 3D modeling and printing, it becomes possible to integrate the various haptic components discussed in the previous chapter into existing prosthetics. Several concepts and prototypes are presented. Furthermore, this chapter explores the creation of affordable and

replicable bio-patches accessible to everyone, along with information on testing and results. It also offers insights into manufacturing techniques and material selection for prosthetics and bio-patches.

This thesis contributes to the understanding and development of haptic for medical innovation, specifically in the field of prosthetics, intended for both experienced and novice users through a DIY kit.

Understanding the role of technology and its accessibility is crucial in today's society and that of tomorrow. It is a significant step in realizing all new projects and must be considered by researchers and businesses. In this first chapter, an analysis and questioning of technological accessibility at various scales are carried out. Starting with technological innovation as a whole, then medical innovation, and finally prosthetics. This thesis provides a comprehensive reflection and encourages the approach to making technology more accessible while linking it to the thesis project.

The second chapter focuses on the field of haptic and takes a first step toward it by exploring various components and their possible uses. It explores different functions and provides simple codes for various uses. Through multiple prototyping and various tests, it offers solutions for implementing different components used for haptic that can be placed on a prosthesis.

The final chapter explores the development of a user-friendly and accessible prosthesis for everyone. This is achieved through selecting materials, a design method, and the design itself. The chapter addresses how to design to cater to a wider audience, how to implement different components into the prosthesis, and how to ensure longevity through clever design and material choices. The second section of this chapter deals with the creation of bio-patches made from accessible and user-friendly bio-materials. Prototyping and material and user tests are included in this thesis.

This thesis may be limited to individuals already present

in these various fields. However, there are numerous possibilities for improvement with the constant evolution of medical innovation and the emerging field of haptic. This first step can be pushed further by creating increasingly advanced kits with new components, code improvement and optimization, and prosthetics designed for such devices.

This thesis is a first step toward haptic and medical innovation in prosthetics by offering a simple DIY kit accessible to everyone. It combines programming, understanding of haptic, 3D design, and bio-materials. Furthermore, this work presents methodological contributions to the integration of haptic into the field of prosthetics. It is accompanied by prototyping with methods to combine innovation, efficiency, and accessibility.

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