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.

DE VINCI INNOVATION CENTER

Artificial Lives

DE VINCI HIGHER EDUCATION

List of Theses

TRISTAN JOURNEL - 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 JOURNEL

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 explores the intersection between haptic technology, prosthetics, and technological accessibility.
The development of a DIY (Do It Yourself) prosthesis 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 prosthesis kit aims to enhance user experiences by providing precise and intuitive sensory feedback.
Throughout this thesis, we will address several important steps, 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.

Contents

Introduction | 1

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.

Figure 1.1: Edwin Smith Papyrus From [1]

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.

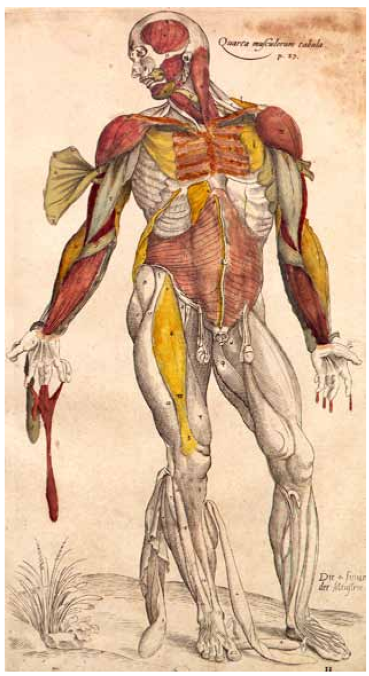

Figure 1.2: A 16th-century Representation of human anatomy by Andreas Vesalius

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 prostheses 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.

Figure 1.3: E

gyptian foot prosthesis over 3000 years ago From [3]

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 Actronika 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 prothesis innovation. Several disciplines - haptic, design and modeling, and bio-materials science - intertwine, making this research topic a multidisciplinary field.

Haptics 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

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...

Finally, a prototyping and testing approach is implemented. A prototype is built and subjected to mechanical assessments and user testing to identify issues and understand needs. This process is repeated until the final version best meets the specified requirements and challenges.

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.

Accessibility to technological and medical innovation

2

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 technological 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].

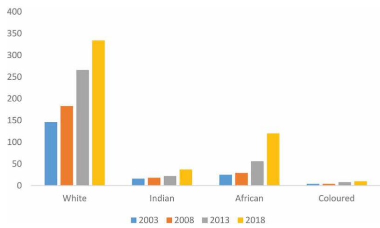

Figure 2.1: E

volution of the number of SouthAfrica prostheses in the 21st century From [26]

According to an article published in "The Lancet" in 2018, "access to medical innovations remains unequal worldwide, 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 approximately 10 pourcent of the world's population. Of those people, 80 pourcent 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 pourcent 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 pourcent 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 pourcent 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.

3 First Step into the Field of Haptic

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 [45]. Furthermore, technological innovations based on the sense of touch and haptic are being developed to assist blind individuals [46][47]. 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 [48], 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 [49][50].

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 [51][52]. It was followed by other virtual reality devices with improved haptic capabilities, such as the HaptX haptic gloves [53].

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 [54]. 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 [55].

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. [56], 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. [57], 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 [58] 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 [59] 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 [60], 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 [61], 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 [62] 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 [63].

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 [64]. 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 [65][66][67][68][69][70].

On the other hand, patients can benefit from rehabilitation through haptic-based exercises, including engaging projects like that of Mark Sivak and his team [71], which offer a hand rehabilitation system integrating interactive games providing haptic feedback to the user. Furthermore, haptic projects specially designed for amputees contribute to their rehabilitation and social reintegration [72]. Finally, the use of haptic for therapeutic purposes is also an avenue being explored [73].

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

We present 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 microcontrollers, 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 Hardware

3.4.1 Microcontrôleur

DRV205 Teensy

3.4.2 Moteur haptique

LRA ERM

3.4.3 Sensors

Simple piezo Flexible Piezo Sound Sensor

3.5 Dispositif

3.6 Software Development

3.6.1 Technical Specifications

The Teensy and DRV2605 are programmed in C++ and are compatible with the Arduino platform. The use of the C language is also possible. Usage libraries are available and provide standard methods for their use. Regarding the DRV2605, numerous examples are provided, covering scenarios from simple vibrations to real-time feedback. Additionally, a wide range of instructions and libraries is available on the website https://www.pjrc.com/teensy/ dedicated to Teensy. This site offers comprehensive resources, including information on using Teensy in the audio domain, which benefits from a unique interface.

3.6.2 Objectives

3.6.3 Implementation

3.7 Evaluation

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

3.7.1 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.

3.7.2 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.

3.8 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.

3.9 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.

3.10 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.

L’haptique au service de la médecine / prothèses DIY | 4

4.1 Introduction

je vais refaire l’intro en fonction de son qu’on a dit durant l’appel

Prostheses

The use of haptics for therapeutic purposesA prosthesis is an artificial device designed to replace a limb, organ, or joint. The term "prosthesis" comes from the Greek word "prosthesis," meaning "the act of adding." The field of prosthetics is considered interdisciplinary, situated at the intersection of engineering, medicine, and biology. It encompasses the design, development, and manufacture of artificial devices intended to replace or enhance the functions of human limbs or other body parts. Modern prostheses go beyond merely replacing the mechanical process of a lost limb. They also contribute to patients’ physical and mental rehabilitation by helping them resume their daily and professional activities [1].

Numerous prostheses exist today, varying in their design, components, and functionality. There are purely aesthetic prostheses designed to visually replace a missing part of the body [2]. Mechanical [3], myoelectric [4], or hydraulic [5] prostheses use different means, such as electrical signals or fluids (liquids or gases), to control the prosthesis and perform precise movements similar to human motion.

Advanced projects focus on neuroprosthetics. Cutting-edge research concentrates on creating neural interfaces that enable direct communication between the prosthesis and the user’s brain [6]. The prosthesis allows for more intuitive control of the prosthetic limb’s movements, bridging the gap between the user’s intentions and the limb’s actions.

BioMaterials and BioPatches

Innovation is crucial in enhancing patient care and seeking more effective treatment solutions in the medical field. Biomaterials and biopatches have emerged as essential areas of research and innovation at the intersection of engineering, medicine, and materials science.

Biomaterials, a class of materials designed to interact harmoniously with biological systems, have catalyzed a revolution in regenerative medicine, surgery, and personalized medicine. Their versatility enables the creation of more advanced prosthetics and implants [7], tissue regeneration [8], and controlled drug release [9]. They have transformed how we approach the design of medical devices and surgical interventions, providing new opportunities to enhance human health.

Simultaneously, biopatches [10], a specific application of biomaterials, have proven to be valuable tools for tissue regeneration, targeted drug delivery, and real-time monitoring of physiological parameters [11]. Known as skin patches, they have evolved from simple adhesive bandages to sophisticated and multifunctional devices. They combine sophisticated biomaterial properties with cutting-edge technologies, opening new perspectives in fields ranging from regenerative medicine to wearable medical monitoring.

The interest in biopatches and biomaterials stems from the desire to improve the quality of life for patients by offering more comfortable and less invasive alternatives to traditional treatments. These areas hold revolutionary potential to enhance individuals' quality of life, transform healthcare, and pave the way for extraordinary medical advances.

This project aims to make the design of bioplastics, biopatches, prostheses, and prosthetic enhancements more accessible to the general public. It focuses on rapid and cost-effective prototyping while providing essential knowledge in the design and manufacturing methods of DIY biopatches and prostheses. It serves as an initial step for anyone interested in engaging in these fields, offering straightforward and affordable solutions to enhance the daily lives of amputees.

4.2 Related Work

Prostheses

The field of prosthetics has witnessed incredible advancements driven by cutting-edge engineering technologies. These developments encompass design, materials, sensor integration, neurology, and accessibility.

Some projects are moving towards personalization. Recent trends emphasize the creation of tailored solutions. With 3D printing and scanning technologies, prosthetics can be custom-made to match the user's unique anatomy, enhancing comfort and functionality. Projects like that of David C. Ackland and his team [1] develop custom 3D-printed prosthetic joints based on scans. Similarly, Naomi C. Paxton and her team [2] craft customized prosthetics after an in-depth patient anatomy study.

In addition to customization and 3D printing, there is a growing focus on patient autonomy. An increasing number of projects offer prosthetics for personal assembly (Do It Yourself, DIY), enabling individuals to design their prostheses. It's exemplified by initiatives such as My Human Kit and Bionicohand [3], which provide detailed tutorials with accessible files for creating personalized forearm prosthetics using 3D printing, a technology within reach of most. Movements like E-nable [4] actively promote this concept and encourage self-reliance.

Others are dedicated to incorporating lightweight, durable, and biocompatible materials, contributing to developing more comfortable and functional prosthetics. In 1974, researcher Sauer and his team [5] explored using porous polyethylene, which can adapt to tissue growth when manufactured in this form. Subsequently, other projects have continued to explore material choices [6][7]. M.-S. Scholz and his team [8] have focused on using composites with an excellent strength-to-weight ratio and outstanding biocompatibility. All these projects aim to mimic the mechanical properties of natural limbs, promoting a more natural and efficient approach.

Sensor integration represents a significant part of prosthetic innovation. Sundaram and his team [9] developed a glove demonstrating that sensors uniformly distributed on the hand can identify individual objects, estimate their weight, and explore the typical tactile patterns that emerge when grasping objects. Prosthetic limbs equipped with various sensors enable users to perceive their environment better. These sensors provide real-time information, such as pressure, temperature, and movement, enhancing the user's awareness and control over the prosthetic limb [10]. Projects like those led by Ting Zhang and his team [11], or Low. C and his colleagues [12] showcase the integration of tactile sensors, allowing users to manipulate delicate objects more effectively and regain a sense of touch lost due to amputation.

BioMaterials and BioPatches

With the emergence of bio-materials, bio-patches technology has arisen as a revolutionary field in medical devices, potentially transforming the way medical treatments are administered and monitored.

In terms of materials, some projects focus on composite bio-materials. The project led by Román A. Pérez and al. [13] creates bio-materials that stimulate/trigger targeted cellular responses critical in tissue regeneration processes. Bio-materials combine different materials to harness their specific properties and are commonly used. For instance, polymer-ceramic composites find applications in dental implants [14].

Integrating electronics into bio-materials and bio-patches is a significant part of the innovation in this field. Eldy Vasquez and al. project [15] explores using mycelium with standard digital fabrication techniques to replace plastics in electronics. Bio-materials are now being designed to incorporate electronics, opening up possibilities in intelligent medical devices [16]. Polymeric bio-materials serve as integral components, including thin-film electronics, in vitro cell culture models, and implantable medical devices [17].

The project by Logesh S and al. [18] employs a double-layered plant-based bio-polymeric patch (bio-patch) with wound healing efficacy and skin-mimicking functions for cutaneous tissue regeneration applications. Enhancing bio-compatibility is a crucial aspect of bio-patch innovation. Researchers are striving to improve the bio-compatibility of bio-materials to reduce immune reactions and minimize the risk of rejection.

Many of these projects are environmentally and sustainability-conscious. There is a growing interest in developing eco-friendly and sustainable bio-materials, focusing on waste reduction and using renewable resources.

Despite the wide range of applications and processes, these techniques still need to be simplified for inexperienced users. They either require the use of expensive equipment, the modification and design of machinery, or extensive knowledge in other fields such as mechanics, design, medicine, or even biochemistry. On the other hand, the project presented in this chapter does not demand advanced knowledge. It relies on simple and cost-effective methods and components, enabling the creation of a self-contained prototype.

4.3 Prosthetics DIY

4.3.1 Objectives

The objective of this 3D design is to provide support for the various haptic components used and to complement a forearm prosthesis. While it is possible to modify an existing prosthesis, this requires 3D design skills on the part of the user and may appear complex due to the wide variety of available prostheses. To accompany the DIY haptic kit, we offer a simple device. It is added to a prosthesis and positioned at different locations on the arm to accommodate various types of amputations. Its design aims to maximize accessibility and facilitate printing or modifications as needed. It allows for integrating multiple components while reducing the bulk they bring.

4.3.2 Materials Used

The use of 3D printing has become increasingly common in the field of prosthetics, primarily due to its flexibility, customization, and production speed. Here is a list of materials commonly used in 3D printing that we have explored for the creation of an additional device to the kit:

PLA, or Polylactic Acid, is one of the most popular materials in 3D printing, especially for beginners. It is known for its ease of printing. Due to its biological origin, PLA is usually considered bio-compatible, making it suitable for applications such as creating prosthetics or temporary medical implants. Moreover, it's one of the least expensive materials for 3D printing, making it a cost-effective choice for beginners and experimental projects. However, it has heat resistance and mechanical strength limitations, which can restrict its use in high-performance applications.

ABS, or Acrylonitrile Butadiene Styrene, is commonly used in 3D printing. His toughness and durability make it a popular choice for various applications. It is known for its mechanical strength and shock resistance, meaning it can withstand high loads and stresses. Furthermore, it can be easily sanded and polished to achieve a smooth and aesthetic finish. However, it can emit toxic fumes and is not biodegradable. ABS is widely used in industrial part production, mechanical components, and functional prototypes.

Polypropylene (PP) is a thermoplastic widely used in 3D printing due to its distinctive characteristics, lightweight nature, and durability. Polypropylene is one of the lightest plastics in 3D printing, making it suitable for lowdensity applications. Polypropylene absorbs very little moisture and exhibits high shock resistance, making it ideal for parts subjected to mechanical stress. However, printing can be challenging and may require specific settings and a compatible printer.

TPU, or Thermoplastic Polyurethane, is a material appreciated in 3D printing for its flexibility, impact resistance, and versatility. Additionally, it's often considered bio-compatible, making it a choice for medical applications and skin contact parts. It effectively resists abrasion, making it suitable for parts prone to wear. However, TPU can be challenging to print due to its elasticity and is generally more expensive than more familiar materials like PLA or ABS.

Nylon is a popular 3D printing material known for its strength and durability. While it is less flexible than TPU, nylon has some flexibility, making it suitable for applications requiring slight deformation. It can be used in various applications, from prototypes to final parts. However, nylon tends to absorb moisture from the air, requiring pre-print drying to avoid issues. It is generally more expensive than common materials like PLA or ABS.

The choice of material will depend on the specific needs of each prosthesis, including the intended function, durability, flexibility, and bio-compatibility. Many tests and prototyping have been conducted to determine the most suitable material.

4.3.3 Modeling

The kit's various components, projects, and prototypes intended for material testing were created using different modeling software. Among them, we find SolidWorks, a modeling software well-known to the general public, and nTopology, a widely used software in medicine for designing lattice structures and complex geometries.

Scans were performed on forearms, feet, and amputated limbs using the Ossür software to enable the printing of amputee sockets, braces, and orthopedic insoles and to conduct material tests.

Orthopedic insoles, sockets, and braces are created from scans and modeled in nTopology. In contrast, prostheses and elements of the DIY kit are designed using SolidWorks.

4.3.4 Implementation

Several prototypes were created, whether to evaluate materials or assess ease of printing and usage. In this regard, auxiliary projects were undertaken, including the design of splints, sockets, and orthopedic insoles tested on patients. Each project presented a unique challenge with specific requirements, enabling the evaluation of materials based on various criteria such as strength, flexibility, cost, and more.

Prototyping for the Kit

Objectives

The first step in the kit involves modifying an accessible online prosthesis. This choice was made due to its simplicity as an initial trial for the KIT. The goal was to find a removable prosthesis that was accessible to all and easily adaptable.

Modeling and Implementation

The main modification concerns the platform holding the cables responsible for finger movement in the prosthesis. It was adapted to accommodate all necessary microcontrollers. The basic structure is retained, but a second level was added to attach a PCB with the components, which can be directly affixed to the platform. The primary aim of this prototype was to integrate these components to ensure ergonomic usability without hindering the user during kit and prosthesis use.

This first prototyping is simple but requires further use. It has been developed to test the various components better to understand the needs and constraints for a second proposal. PLA is a suitable material for this device.

Kit Device

Objectives

The second prototype is a device designed to complement a forearm prosthesis. It is simpler to reach a broader audience by providing a device that can be added to an existing prosthesis rather than attempting to modify a prosthesis used by a small number of individuals and potentially not meeting their specific needs. This concept underpins the design of the second device.

Modeling and Implementation

Its design is based on a device positioned on the arm, whether on the forearm or the upper part beyond the elbow. Similar to a bracelet, it wraps around the arm. The base diameter is adjustable in the design phase or directly based on the chosen material's flexibility. The top part is flat and hollow, accommodating the PCB with various controllers required for the kit. Holes are provided for routing cables connecting sensors to microcontrollers, and notches on the sides allow the device to be fastened to the arm using Velcro.

This device stands out for its design, modification, and use simplicity. Its geometry allows it to be printed with various materials, eliminating the risk of poor printing. Its purpose is not to replace or modify an existing prosthesis but to complement it, ensuring compatibility with a wide range of prosthesis types. For this device, ABS and nylon are recommended for their strength, while PP offers excellent flexibility and ease of movement.

Device for Various Sensors

Objectives

In addition to the device for supporting controllers, another device was conceived to attach various types of sensors. It should be user-friendly and compatible with a wide range of prostheses. In addition to the platform designed to support controllers, another device intended to attach various types of sensors was envisioned. It should be accessible and adaptable to as many prostheses as possible.

Modeling and Implementation

The design of this device follows the same principle as the previous one. It is an open ring designed to slide onto the end of the prosthesis, allowing it to be positioned on the prosthetic finger. TPU is strongly recommended for its high flexibility. A flat base, bordered by right-angled edges, allows for the insertion of various sensors. For circular piezoelectric sensors, the bottom has a corresponding circular shape.

In addition to these various devices, using highly flexible electrical wires to connect different components is highly recommended. They offer the ability to track the user's movements without the risk of breaking, such as Adafruit Stainless Thin Conductive Yarn for sewing.

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 is 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 (figure ...).

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 biomaterials 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

Alginate is 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 biocompatibility, 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 biomaterials with diverse properties.

4.4.4 Fabrication Process

Bio-Materials Several approaches have been implemented to create the most efficient bio-plastic possible. These experiments have involved various combinations of quantities, preparation methods, and materials used.

To optimize the results, it is imperative to maintain a high level of cleanliness for the instruments and surfaces used during preparation. Therefore, it is essential to wash hands thoroughly, disinfect tools with alcohol, and work in a properly ventilated environment.

A standardized protocol was followed throughout the bio-plastic manufacturing process. This protocol includes the component mixing step, a variable resting period, and heating and agitation using a magnetic stirrer.

Place them on a flat, clean surface, avoiding glass surfaces that could make removal more difficult. Applying two drops of antifungal oil prevents mold growth. The drying time required depends on the material used, but typically, it takes between 1 and 3 days once the texture has solidified.

Bio-Patches After manufacturing the bio-plastics, we started the design of the bio-patches. These bio-patches

1st combination	2nd combination	3rd combination	4th combination	5th combination
6g alginate 200g distilled water 20 g glycerine	2.5g Gellan 50g Distilled water 5g Glycerin	2.5g Gellan 50g Distilled water 5g Glycerin	6g Gelatin 200 30g Distilled water 6.8g Glycerin	6g Gelatin 250 30g Distilled water 6.8g Glycerin

Figure 4.1: Recipes for the creation of biomaterials

aim to transmit vibrations from LRA or ERM motors to individuals while avoiding direct contact with the skin that could cause discomfort or damage to the components. To achieve this, we created a bioplastic structure surrounding the engine like a sandwich.

The patch itself consists of two layers. The lower layer is directly attached to the skin, and the haptic motor is positioned above this first layer. It is then covered by the second layer of biomaterial, which adheres to the edges of the first layer it is in contact with, as illustrated in this figure.

To create the bio-patch, cut pieces of bio-plastic using a cutter. The shape and size depend on the user's choice, but a circular shape provides better adhesion than a rectangle or a square. Moisturize the area of the body where the patch will be applied. Next, place a first layer of bio-plastic, moisten it, position the haptic motor on this first layer, and then cover it with the upper layer of bio-plastic, which is also moistened to promote adhesion between the two layers.

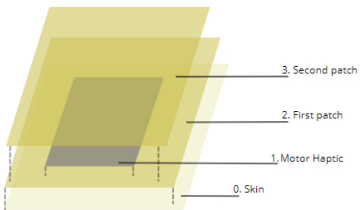

Figure 4.2: Diagram of the Biopatches and its various layers

4.5 Evaluation

Prostheses

Regarding prosthetics, a more comprehensive evaluation was conducted. We compared materials and prosthetic manufacturing methods on several aspects:

Multiple printing tests were conducted to determine the easiest-to-use material while providing sufficient quality. In addition to the device for the DIY kit, various types of projects were undertaken, including splints, sockets for amputees, and foot orthoses, to be tested. The standout materials are ABS and PLA.

Tests of strength and flexibility were performed. Materials offering the most strength in the face of significant mechanical stress are nylon and ABS. However, PP and PETG offer substantial strength due to their flexibility, although PETG can occasionally be too flexible. It is also possible to heat some materials, such as PLA, ABS, and nylon, to reshape the piece and make it more comfortable.

User comfort depends on individual preferences. If the user seeks more mobility, they should opt for a softer prosthesis, while if they prioritize durability, they will choose a sturdier prosthesis.

Considering all these factors, the materials that appear most suitable for the kit's device are ABS and PP. Nevertheless, the choice will depend on the user's specific needs and intended use.

Bio-Patches

Several tests involving different recipes were conducted. Adjusting the proportions makes it possible to modify the material's elasticity, durability, and resistance to friction. Additionally, obtaining other parameters is conceivable by varying the cooking time and temperature and altering the thickness of the future patch.

Multiple tests were performed, exploring different combinations to achieve the best possible result:

Test 1: Place the motor between two layers of gelatin 250, with a smaller layer underneath in contact with the skin and a more significant layer covering the whole. Adherence to the skin is satisfactory, but it may detach in the presence of excessive hair.

Test 2: Position the motor between a more extensive upper layer of gelatin 250 and a lower layer of gellan.

There is good adherence between the layers but weak adherence to the skin.

Test 3: Position the motor between two layers of gelatin 200, with a smaller layer underneath in contact with the skin and a larger layer covering the whole.

Test 4: Place the motor between a larger upper layer of gelatin 250 and a lower alginate layer. Alginate adheres well to the skin and serves as an effective lower layer.

Test 5: Position the motor between two layers of gelatin 250, with a smaller layer underneath in contact with the skin and a more significant layer covering the whole.

Test 6: Place the motor between a more extensive upper layer of gellane and a lower alginate layer.

In summary of the trials conducted with bio-patches, it appears that the larger the lower surface, the stronger the adherence to the skin. Furthermore, if the upper side is smaller than the lower downside, this enhances the cohesion between the two layers and reduces external friction. It is recommended to use gelatin as the material for the lower layer, given its greater flexibility and flexibility compared to other materials, which is particularly crucial for absorbing deformations. To enhance adhesion, it is advisable to moisten both the skin and the patches while ensuring that water droplets are avoided. A significant improvement in adhesion is observed on arms with fewer hairs.

4.6 Limitations

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 biomaterials, 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 possible to optimize it by improving the design of the device added to the prosthesis. This approach aims to make it more adaptable to various types of amputations. Furthermore, improvements can be made by exploring multiple materials, seeking to reconcile comfort, flexibility, and strength, and even integrating new innovative 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 biopatches. 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 biopatches accessible to everyone, along with information on testing and results. It also offers insights

into manufacturing techniques and material selection
for prosthetics and biopatches.

5 Conclusion

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.

Acknowledgements

It's with deep gratitude that I pick up the pen today to express my sincere thanks to all those who have contributed to the realization of this Master's Engineering thesis. This work represents the culmination of several years of effort and learning, and I am honored to share this moment with you.

Firstly, I would like to thank Dr. Marc TEYSSIER and Dr. Clément DUHART for their invaluable guidance, constant support, and insightful advice. Your expertise and passion for research have been a source of inspiration.

My thanks also go to the entire faculty of the DVIC, including the PI and doctoral students. Your high-quality teaching and willingness to share knowledge have enriched my academic and professional journey.

I want to express my gratitude to PIVOT Prosthetics and Orthotics for the internship opportunity they provided. This experience strengthened my determination to work in the medical field and allowed me to complete the research work for this thesis.

I want to thank my colleagues from DVIC for their teamwork, exchanges, and mutual support. Our discussions and debates have shaped my understanding of the topics covered in this thesis, and I am honored to have shared this experience with all of you.

Finally, I would like to thank Violette ANICET-MERVEILLEUX for her help with the bio-patches and bio-materials for this project. And I would like to express my gratitude to all those who have contributed, directly or indirectly, to completing this research work. Your advice, feedback, and contributions have been invaluable in accomplishing this thesis.

Finally, I would like to express my deep appreciation to my friends and family for their continuous support and positivity during my studies.

References

[1] Joost J. van Middendorp, Gonzalo M. Sanchez, and Alwyn L. Burridge. 'The Edwin Smith papyrus: a clinical reappraisal of the oldest known document on spinal injuries'. eng. In: *European Spine Journal: Official Publication of the European Spine Society, the European Spinal Deformity Society, and the European Section of the Cervical Spine Research Society* 19.11 (Nov. 2010), pp. 1815–1823. DOI: 10.1007/s00586-010-1523-6 (cited on page 4).

[2] Fabio Zampieri et al. 'Andreas Vesalius: Celebrating 500 years of dissecting nature'. en. In: *Global Cardiology Science and Practice* 2015.5 (Oct. 2015), p. 66. DOI: 10.5339/gcsp.2015.66. (Visited on 10/24/2023) (cited on page 4).

[3] *Prosthesis*. en. Page Version ID: 1181407711. Oct. 2023. URL: https://en.wikipedia.org/w/index.php?title=Prosthesis&oldid=1181407711 (visited on 10/24/2023) (cited on page 5).

[4] *Coapt - Myoelectric Pattern Recognition for Upper Limb Prostheses*. URL: https://coaptengineering.com/ (visited on 10/24/2023) (cited on page 5).

[5] *PSYONIC*. en-US. URL: https://www.psyonic.io (visited on 10/24/2023) (cited on page 5).

[6] *Advanced Prosthetics Made Accessible: How PSYONIC Developed a Bionic Hand Using Additive Manufacturing | Formlabs*. URL: https://formlabs.com/blog/psyonic-advanced-prosthetics-additive/?utm_source=youtube&utm_medium=social&utm_campaign=yto-psyonic (visited on 10/24/2023) (cited on page 5).

[7] *New advances for haptic rendering: state of the art | SpringerLink*. URL: https://link.springer.com/article/10.1007/s00371-016-1324-y (visited on 10/24/2023) (cited on page 6).

[8] Interhaptics. *Haptics for Mobile: the best practices for Android and iOS*. en. June 2021. URL: https://medium.com/nerd-for-tech/haptics-for-mobile-the-best-practices-for-android-and-ios-d2aa72409bdd (visited on 10/24/2023) (cited on page 6).

[9] *What's under the hood of the DualSense?* URL: https://www.actronika.com/post/whats-under-the-hood-of-the-dualsense (visited on 10/24/2023) (cited on page 6).

[10] *Skinetic by Actronika*. URL: https://www.skinetic.actronika.com/ (visited on 10/24/2023) (cited on page 6).

[11] Purdue News Service. *New flexible, transparent, wearable bio-patch, improves cellular observation, drug delivery*. en. URL: https://www.purdue.edu/newsroom/releases/2018/Q4/new-flexible,-transparent,-wearable-

bio-patch,-improves-cellular-observation,-drug-delivery.html (visited on 10/24/2023) (cited on page 6).

[12] *Mending broken hearts*. en. Nov. 2020. URL: https://www.uts.edu.au/partners-and-community/alumni-and-supporters/alumni/tower/stay-connected/mending-broken-hearts (visited on 10/24/2023) (cited on page 7).

[13] Simeon Keates and Shari Trewin. 'Effect of age and Parkinson's disease on cursor positioning using a mouse'. In: *Proceedings of the 7th international ACM SIGACCESS conference on Computers and accessibility*. Assets '05. New York, NY, USA: Association for Computing Machinery, Oct. 2005, pp. 68–75. DOI: 10.1145/1090785.1090800. (Visited on 10/24/2023) (cited on page 11).

[14] Shari Trewin. 'Automating accessibility: the dynamic keyboard'. In: *ACM SIGACCESS Accessibility and Computing* 77-78 (Sept. 2003), pp. 71–78. DOI: 10.1145/1029014.1028644. (Visited on 10/25/2023) (cited on page 11).

[15] *Developing steady clicks: | Proceedings of the 8th international ACM SIGACCESS conference on Computers and accessibility*. URL: https://dl.acm.org/doi/abs/10.1145/1168987.1168993 (visited on 10/25/2023) (cited on page 11).

[16] *Physical accessibility of touchscreen smartphones | Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility*. URL: https://dl.acm.org/doi/abs/10.1145/2513383.2513446 (visited on 10/25/2023) (cited on pages 11, 14).

[17] *Sensitive and Energetic IoT Access Control for Managing Cloud Electronic Health Records | IEEE Journals & Magazine | IEEE Xplore*. URL: https://ieeexplore.ieee.org/document/8753502 (visited on 10/25/2023) (cited on page 12).

[18] Sheetal Vatari, Aarti Bakshi, and Tanvi Thakur. 'Green house by using IOT and cloud computing'. In: *2016 IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT)*. May 2016, pp. 246–250. DOI: 10.1109/RTEICT.2016.7807821. (Visited on 10/25/2023) (cited on page 12).

[19] Andreas Kamilaris et al. 'Agri-IoT: A semantic framework for Internet of Things-enabled smart farming applications'. In: *2016 IEEE 3rd World Forum on Internet of Things (WF-IoT)*. Dec. 2016, pp. 442–447. DOI: 10.1109/WF-IoT.2016.7845467. (Visited on 10/25/2023) (cited on page 12).

[20] *Les meilleurs IoT agricole - SMAG*. URL: https://smag.tech/blog/meilleurs-iot/ (visited on 10/25/2023) (cited on page 12).

[21] Meredith Ringel Morris. 'AI and accessibility'. en. In: *Communications of the ACM* 63.6 (May 2020), pp. 35–37. DOI: 10.1145/3356727. (Visited on 10/25/2023) (cited on page 12).

[22] *Comment la Chine se sert de la technologie pour lutter contre le COVID-19 – et renforcer son contrôle de la population*. fr. Apr. 2020. URL: https://www.amnesty.org/fr/latest/news/2020/04/how-china-used-technology-to-combat-

covid-19-and-tighten-its-grip-on-citizens/ (visited on 10/25/2023) (cited on page 12).

[23] *The complicated truth about China's social credit system | WIRED UK*. URL: https://www.wired.co.uk/article/china-social-credit-system-explained (visited on 10/25/2023) (cited on page 12).

[24] W3C Web Accessibility Initiative (WAI). *Introduction à l'accessibilité du web*. fr. URL: https://www.w3.org/WAI/fundamentals/accessibility-intro/fr (visited on 10/25/2023) (cited on page 13).

[25] Shari Trewin et al. 'Accessibility challenges and tool features: an IBM Web developer perspective'. en. In: *Proceedings of the 2010 International Cross Disciplinary Conference on Web Accessibility (W4A)*. Raleigh North Carolina: ACM, Apr. 2010, pp. 1–10. DOI: 10.1145/1805986.1806029. (Visited on 10/25/2023) (cited on page 14).

[26] *Exploring national human resource profile and trends of Prosthetists/Orthotists in South Africa from 2002 to 2018 - PMC*. URL: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7480577/ (visited on 10/25/2023) (cited on pages 15, 16).

[27] Kara Hanson et al. 'The Lancet Global Health Commissions'. fr. In: 10 (2022) (cited on page 15).

[28] *The Fragility of Legitimacy: Access to Health Care in Manantali, Mali | SpringerLink*. URL: https://link.springer.com/chapter/10.1007/978-3-031-25592-2_4 (visited on 10/25/2023) (cited on page 15).

[29] Arne H. Eide and Tone Øderud. 'Assistive Technology in Low-Income Countries'. en. In: *Disability & International Development: Towards Inclusive Global Health*. Ed. by Malcolm Maclachlan and Leslie Swartz. New York, NY: Springer US, 2009, pp. 149–160. DOI: 10.1007/978-0-387-93840-0_10. (Visited on 10/25/2023) (cited on page 16).

[30] *Provision of prosthetic and orthotic services in low-income countries: A review of the literature - Colette S Harkins, Anthony McGarry, Arjan Buis, 2013*. URL: https://journals.sagepub.com/doi/full/10.1177/0309364612470963 (visited on 10/25/2023) (cited on page 16).

[31] *L'indicateur d'accessibilité potentielle localisée (APL) | Direction de la recherche, des études, de l'évaluation et des statistiques*. URL: https://drees.solidarites-sante.gouv.fr/sources-outils-et-enquetes/lindicateur-daccessibilite-potentielle-localisee-apl (visited on 10/25/2023) (cited on pages 16, 19).

[32] *Are Patents Impeding Medical Care and Innovation? | PLOS Medicine*. URL: https://journals.plos.org/plosmedicine/article?id=10.1371/journal.pmed.1000208 (visited on 10/25/2023) (cited on page 16).

[33] *Public satisfaction with health care system in 30 countries: The effects of individual characteristics and social contexts - ScienceDirect*. URL: https://www.sciencedirect.com/science/article/abs/pii/S0168851021002062 (visited on 10/25/2023) (cited on page 16).

[34] Amina Fefe Dia. 'Projet de stratégie mondiale pour la santé numérique 2020-2025'. fr. In: () (cited on page 17).

[35] *COVID-19, IP and access: Will the current system of medical innovation and access to medicines meet global expectations? - Olga Gurgula, Wen H Lee, 2021*. URL: https://journals.sagepub.com/doi/full/10.1177/1741134321993182 (visited on 10/25/2023) (cited on page 17).

[36] *Experiences of providing prosthetic and orthotic services in Sierra Leone – the local staff's perspective: Disability and Rehabilitation: Vol 34, No 24*. URL: https://www.tandfonline.com/doi/abs/10.3109/09638288.2012.667501 (visited on 10/25/2023) (cited on page 18).

[37] Mike Mitka. 'Advocates seek better insurance coverage for amputees needing limb prostheses'. eng. In: *JAMA* 299.18 (May 2008), pp. 2138–2140. DOI: 10.1001/jama.299.18.2138 (cited on page 18).

[38] Katherine Etter, Matthew Borgia, and Linda Resnik. 'Prescription and repair rates of prosthetic limbs in the VA healthcare system: implications for national prosthetic parity'. en. In: *Disability and Rehabilitation: Assistive Technology* 10.6 (Nov. 2015), pp. 493–500. DOI: 10.3109/17483107.2014.921246. (Visited on 10/25/2023) (cited on page 18).

[39] Chhabi Lal Ranabhat and Mihajlo Jakovljevic. 'Sustainable Health Care Provision Worldwide: Is There a Necessary Trade-Off between Cost and Quality?' en. In: *Sustainability* 15.2 (Jan. 2023). Number: 2 Publisher: Multidisciplinary Digital Publishing Institute, p. 1372. DOI: 10.3390/su15021372. (Visited on 10/25/2023) (cited on page 19).

[40] *WHO standards for prosthetics and orthotics*. en. URL: https://www.who.int/publications-detail-redirect/9789241512480 (visited on 10/25/2023) (cited on page 19).

[41] 'Promouvoir l'accès aux technologies médicales et l'innovation'. fr. In: () (cited on page 19).

[42] *Access to prosthetic devices in developing countries: Pathways and challenges | IEEE Conference Publication | IEEE Xplore*. URL: https://ieeexplore.ieee.org/abstract/document/7343953 (visited on 10/25/2023) (cited on page 19).

[43] *Why Limbs - LIMBS INTERNATIONAL*. URL: https://www.limbsinternational.org/why-limbs.html (visited on 10/25/2023) (cited on page 19).

[44] Tauseef Gulrez et al. 'A Hands-Free Interface for Controlling Virtual Electric-Powered Wheelchairs'. en. In: *International Journal of Advanced Robotic Systems* 13.2 (Mar. 2016), p. 49. DOI: 10.5772/62028. (Visited on 10/25/2023) (cited on page 19).

[45] Javier Jiménez et al. 'Biography of Louis Braille and Invention of the Braille Alphabet'. en. In: *Survey of Ophthalmology* 54.1 (Jan. 2009), pp. 142–149. DOI: 10.1016/j.survophthal.2008.10.006. (Visited on 10/26/2023) (cited on page 24).

[46] Christophe Ramstein. 'Combining haptic and braille technologies: design issues and pilot study'. en. In: *Proceedings of the second annual ACM conference on Assistive technologies - Assets '96*. Vancouver, British Columbia, Canada: ACM Press, 1996, pp. 37–44. DOI: 10.1145/228347.228355. (Visited on 10/26/2023) (cited on page 24).

[47] *BrailleBand: Blind support haptic wearable band for communication using braille language | IEEE Conference Publication | IEEE Xplore*. URL: https://ieeexplore.ieee.org/document/8122806 (visited on 10/26/2023) (cited on page 24).

[48] David Escobar-Castillejos et al. 'A Review of Simulators with Haptic Devices for Medical Training'. en. In: *Journal of Medical Systems* 40.4 (Apr. 2016), p. 104. DOI: 10.1007/s10916-016-0459-8. (Visited on 10/26/2023) (cited on page 25).

[49] Dirk Van Baelen et al. 'Evaluation of a Haptic Feedback System for Flight Envelope Protection'. en. In: *AIAA Scitech 2019 Forum*. San Diego, California: American Institute of Aeronautics and Astronautics, Jan. 2019. DOI: 10.2514/6.2019-0367. (Visited on 10/26/2023) (cited on page 25).

[50] *Haptic technology*. en. Page Version ID: 1181358147. Oct. 2023. URL: https://en.wikipedia.org/w/index.php?title=Haptic_technology&oldid=1181358147 (visited on 10/26/2023) (cited on page 25).

[51] Abdulmotaleb El Saddik. *Haptics Rendering and Applications*. en. Google-Books-ID: zYqfDwAAQBAJ. BoD – Books on Demand, Jan. 2012 (cited on page 25).

[52] Ulrik SöDerströM et al. 'Haptic feedback in first person shooter video games'. In: *Proceedings of the 33rd European Conference on Cognitive Ergonomics*. ECCE '22. New York, NY, USA: Association for Computing Machinery, Oct. 2022, pp. 1–6. DOI: 10.1145/3552327.3552333. (Visited on 10/25/2023) (cited on page 25).

[53] HaptX Admin. *HaptX launches HaptX Gloves DK2 to bring true-contact haptics to VR and robotics*. en-US. Jan. 2021. URL: https://haptx.com/dk2-release/ (visited on 10/26/2023) (cited on page 25).

[54] *Nokia 5800 XpressMusic*. en. Page Version ID: 1171315817. Aug. 2023. URL: https://en.wikipedia.org/w/index.php?title=Nokia_5800_XpressMusic&oldid=1171315817 (visited on 10/26/2023) (cited on page 25).

[55] *Good Vibrations: How Apple Dominates the Touch Feedback Game | iFixit News*. fr. Oct. 2023. URL: https://fr.ifixit.com/News/16768/apple-taptic-engine-haptic-feedback (visited on 10/26/2023) (cited on page 25).

[56] Seongkook Heo, Jaeyeon Lee, and Daniel Wigdor. 'PseudoBend: Producing Haptic Illusions of Stretching, Bending, and Twisting Using Grain Vibrations'. en. In: *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. New Orleans LA USA: ACM, Oct. 2019, pp. 803–813. DOI: 10.1145/3332165.3347941. (Visited on 10/26/2023) (cited on page 26).

[57] Donald Degraen et al. ‘Weirding Haptics: In-Situ Prototyping of Vibrotactile Feedback in Virtual Reality through Vocalization’. In: *The 34th Annual ACM Symposium on User Interface Software and Technology*. UIST ’21. New York, NY, USA: Association for Computing Machinery, Oct. 2021, pp. 936–953. DOI: 10.1145/3472749.3474797. (Visited on 10/25/2023) (cited on page 26).
[58] *Syntacts: Open-Source Software and Hardware for Audio-Controlled Haptics*. en-US. URL: https://ieeexplore.ieee.org/document/9117187 (visited on 10/26/2023) (cited on page 26).
[59] Paul Strohmeier et al. ‘Sketching On-Body Interactions using Piezo-Resistive Kinesiology Tape’. en. In: *Proceedings of the Augmented Humans International Conference*. Kaiserslautern Germany: ACM, Mar. 2020, pp. 1–7. DOI: 10.1145/3384657.3384774. (Visited on 10/26/2023) (cited on page 26).
[60] Dennis Wittchen et al. ‘TactJam: An End-to-End Prototyping Suite for Collaborative Design of On-Body Vibrotactile Feedback’. In: *Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI ’22. New York, NY, USA: Association for Computing Machinery, Feb. 2022, pp. 1–13. DOI: 10.1145/3490149.3501307. (Visited on 10/25/2023) (cited on page 26).
[61] *A Novel Thick-Film Piezoelectric Slip Sensor for a Prosthetic Hand*. en-US. URL: https://ieeexplore.ieee.org/document/4154666 (visited on 10/26/2023) (cited on page 27).
[62] N. Muridan et al. ‘Texture sensor for a prosthetic hand’. en. In: *Procedia Engineering* 5 (2010), pp. 605–608. DOI: 10.1016/j.proeng.2010.09.182. (Visited on 10/26/2023) (cited on page 27).
[63] Kouta Minamizawa, Domenico Prattichizzo, and Susumu Tachi. ‘Simplified design of haptic display by extending one-point kinesthetic feedback to multipoint tactile feedback’. In: *2010 IEEE Haptics Symposium*. ISSN: 2324-7355. Mar. 2010, pp. 257–260. DOI: 10.1109/HAPTIC.2010.5444646. (Visited on 10/26/2023) (cited on page 27).
[64] Arnaud Lelevé, Troy McDaniel, and Carlos Rossa. ‘Haptic Training Simulation’. In: *Frontiers in Virtual Reality* 1 (July 2020), p. 3. DOI: 10.3389/frvir.2020.00003. (Visited on 10/26/2023) (cited on page 27).
[65] *The Role of Haptics in Medical Training Simulators: A Survey of the State of the Art | IEEE Journals & Magazine | IEEE Xplore*. URL: https://ieeexplore.ieee.org/document/5453367 (visited on 10/26/2023) (cited on page 27).
[66] Ross E. Willis et al. ‘Virtual Reality Simulators: Valuable Surgical Skills Trainers or Video Games?’ en. In: *Journal of Surgical Education* 71.3 (May 2014), pp. 426–433. DOI: 10.1016/j.jsurg.2013.11.003. (Visited on 10/26/2023) (cited on page 27).
[67] Cléber G. Corrêa et al. ‘Haptic interaction for needle insertion training in medical applications: The state-of-the-art’. en. In: *Medical Engineering & Physics*

63 (Jan. 2019), pp. 6–25. DOI: 10.1016/j.medengphy.2018.11.002. (Visited on 10/26/2023) (cited on page 27).

[68] David Escobar-Castillejos et al. 'A Review of Simulators with Haptic Devices for Medical Training'. en. In: *Journal of Medical Systems* 40.4 (Apr. 2016), p. 104. DOI: 10.1007/s10916-016-0459-8. (Visited on 10/26/2023) (cited on page 27).

[69] Ravikiran Singapogu et al. 'A Perspective on the Role and Utility of Haptic Feedback in Laparoscopic Skills Training'. English. In: *Critical Reviews™ in Biomedical Engineering* 42.3-4 (2014). Publisher: Begel House Inc. DOI: 10.1615/CritRevBiomedEng.2014011701. (Visited on 10/26/2023) (cited on page 27).

[70] Kevin Kunkler. 'The role of medical simulation: an overview'. en. In: *The International Journal of Medical Robotics and Computer Assisted Surgery* 2.3 (Sept. 2006), pp. 203–210. DOI: 10.1002/rcs.101. (Visited on 10/26/2023) (cited on page 27).

[71] *Haptic system for hand rehabilitation integrating an interactive game with an advanced robotic device | IEEE Conference Publication | IEEE Xplore*. URL: https://ieeexplore.ieee.org/abstract/document/5444615 (visited on 10/26/2023) (cited on page 27).

[72] *Pilot testing of a haptic feedback rehabilitation system on a lower-limb amputee*. en-US. URL: https://ieeexplore.ieee.org/abstract/document/4906637/ (visited on 10/26/2023) (cited on page 28).

[73] Cati Vaucelle, Leonardo Bonanni, and Hiroshi Ishii. 'Design of haptic interfaces for therapy'. en. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. Boston MA USA: ACM, Apr. 2009, pp. 467–470. DOI: 10.1145/1518701.1518776. (Visited on 10/26/2023) (cited on page 28).