Malleable Media:

Towards Shape-changing Interfaces

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Towards Shape-changing Interfaces

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ABSTRACT

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Malleability is a distinctive characteristic of the digital world. Users can freely deform virtual objects, manipulate data, or rearrange elements on a desktop. However, such malleable qualities are not reflected in the objects and interfaces we use to interact with such elements. They are static and rigid. Recently, shape-changing materials have gained interests in both Human-Computer Interaction and media art as a new way to merge the physical and the virtual. Shape-changing materials allow users to physically manipulate and deform physical interfaces capable of transforming their materiality to represent digital data. However, even if this research area is growing, several aspects are still not clear. These include aspects such as design metaphors, enabling technologies, content design, and human perception. This thesis contributes to these open questions through empirical research based on two main case studies. The first is Vital+Morph, a shape-changing interface used for displaying streams of digital data between remote locations. In contrast with previous work, we propose a bio-inspired approach for designing interfaces to encode digital data better physically and represent them through deformations. To identify a novel application area of shape-changing interfaces, such as remote monitoring of a patient, we propose a scenario-based approach and subsequent investigation of the social impact of shape-changing interfaces through a public exhibition. The results show the potentials and criticalities of such interfaces, which can be very strong but also very invasive. The second is Volflex++. This system can reproduce the geometrical and material qualities of virtual objects through self-deformation. We present the implementation of the system and a user study based on psychophysics. The results show that users can accurately discriminate small changes, and the perception of size and rigidity is in line with the one that occurs with real materials. Such findings are used to design a proof-of-concept application for the creation of virtual-physical materials. Through this work, we propose the concept of Malleable Media to better define and emphasize the characteristics of shape-changing materials as a new type of haptic media, that can offer new ways to relate with the digital world and generate new forms of media art.

1. INTRODUCTION

This thesis introduces the conceptual framework of malleable media through an explorative study of the design, technological, and perceptual characteristics of this emerging media enabled by the rise of shape-changing materials. We frame our work in a phenomenon we define as the *wrap of the virtual and the physical world.* Most of the research on Virtual Reality focused on making virtual experiences more physical and real for examples with the use of haptic interfaces. However, with the emergence of shape-changing materials, Internet of Things (IoT) technologies, and robots we witness a situation where physical and real experiences feel and appear to be like the virtual ones.

Malleability is a distinctive characteristic of the digital world. Users can freely navigate, and rearrange symbols on a desktop, or create and manipulate virtual objects. However, such dynamic qualities are not reflected in the objects and interfaces we use to interact with digital processes, which are usually static and rigid. The Cambridge Dictionary defines *malleable* as an adjective that describes a substance that can be easily changed into a new shape[1]. Malleable also refer to objects or materials that can be altered or controlled by outside forces or influences. Malleable media can also be seen as an extension of the idea of 'tangible media'. However, in the definition of Ishii et al. [1] 'tangible' just implies the presence of digital data in the physical world to help people relate to their existence. With 'malleable' we refer to specific qualities of materials and their possibilities of being shaped and manipulated. Malleable media present contents through their materiality. They can be shaped and manipulated either by humans through their hands, and by digital information, which can deter-

[1] `https://dictionary.cambridge.org/dictionary/english/malleable`

mine their physical appearance. In malleable media, the haptic qualities are more prominent and important than the visual characteristics or just a physical presence. This thesis aims to provide answers to three main questions.

1. *How to realize malleable media*? This includes problematics related to both design and engineering. As for design, we explore the use of bio-inspired metaphors for designing dynamic systems based on deformable and shape-changing materials. As for engineering, we propose two mechanisms to realize several changes of shape and materiality, such as change of geometry, change of size and rigidity.

2. *How they are perceived by humans*? Our research focuses on the haptic qualities of malleable media as created through shape-changing materials. This marks a difference with previous studies, who looked at shape-change and data physicalization from the visual point of view. We use methods from psychophysics to study changes in shape and materiality. However, perception is not only through senses but also on the impact that shape-changing materials can have on our reality. We present a study using media art installations as a way to develop user studies for investigating social and perceptual characteristics of emerging technologies.

3. *Which content they can present and how*? We propose different possible contents that can be presented through malleable media. We position this contribution in the context of Media Art and derive our approach from emerging practices of artists using digital technologies. Content design is still an open issue for shape-changing materials and we aim to propose several new directions, such physical representation of biometric data, and the creation of novel hybrid virtual-physical objects.

We discuss such aspects through two case studies. The first, Vital+Morph [2, 3] is a prototype for a shape-changing material used to make biomedical data physical. Remote users can experience data through the change of geometry, which generates haptic feedback. The second, Volflex++ [4] shows a novel system that can enable the presentation of virtual objects and materials physically through changes in size and rigidity. By discussing the process of implementation, and the evaluation of both technical and human factors we derive a series of design guidelines that can be used to think and create malleable media and how they can enable new forms of media art.

1.1 Structure of the Thesis

The present thesis is structured as follows:

- *Background*: We define the conceptual and technological background to identify the landscape where this study is placed. Through this chapter we outline the concept of embodied cognition, the idea of media as developed by Marshall McLuhan, define the characteristics of Virtual Reality and the world as represented by data. We then present how media artists have dealt with virtual reality to create new experiences. Finally, we unfold the main technologies that enable the emergence of malleable media, such as shape-changing interfaces and Internet of Things devices.

- *Related Work*: We review the main literature in areas that pertain our study. This includes application areas like data physicalization, haptic interfaces, and the different technologies used for achieving different types of shape-change.

- *Methods*: We present the methodologies used to develop our study. We first describe what bio-inspired design is and which are its implications. Second, we present a specific technology used in one of our studies. Third, we outline the main findings and techniques used for study the haptic perception of materials and objects. Lastly, we define a mix-method of research based on the observations and interview of users in the context of a media art installation.

- *Case Study I*: We present Vital+Morph, a prototype for a shape-change material. Through this system, we propose an application scenario in the context of remote monitoring and propose a user study to test and understand such scenario in action through an extended study in media arts festivals.

- *Case Study II*: We present Volflex++, a novel system that can support the creation of physical-virtual materials. Through a psychophysical experiment with twenty subjects, we test the haptic resolution of such a system. We also introduce a proof-of-concept application to show how virtual objects can be presented through this system.

- *Discussion*: In this last chapter, we outline the common characteristics of Vital+Morph and Volflex++ by the definition of a series of design guidelines. We then discuss how malleable media can be used to enable new types of media artworks.

2. BACKGROUND

Through this chapter, we lay the main conceptual background of the thesis. We will show which theories and practices led to the emergence of the concept of shape-changing interfaces and materials. Especially, we will look at how engineers, computer scientists, and media artists have contributed to developing such concepts through their work. Finally, we will discuss how emerging technologies such as shape-changing interfaces and distributed intelligent devices are changing our world and therefore challenge our perception and ideas about digital media. Such discussion will help us to place the discussion on malleable media in the context of the contemporary technological and theoretical landscape.

2.1 The World as Perceived by Touch: Embodied Cognition

The way we understand and interpret the world is deeply rooted in our physical bodies. How we, as humans, feel objects and the environment drives the way how we think and behave. Such view on cognitive processes and intelligence is known as *embodied cognition* [5]. According to the hypothesis of embodied cognition, we cannot consider intelligence as a process that occurs only inside the brain. Cognition is extended into artifacts and social systems. Cognition is dynamic and it is produced through continuous engagement with tools, language, and other human and non-human agents. This also includes computational tools, artifacts, and environments. We can look at language, which is always built upon our physical interactions with the world. For instances, when we describe relations with other humans, we use words related to the perception of texture, weight, material properties, and heat. At the root of our language is how we feel the world through touch. Touch is used to gain an understanding of the world, through exploration and manipulation, and at the same time to convey information among people, like shaking hands, or to show feelings and emotion between people (Figure 2.1).

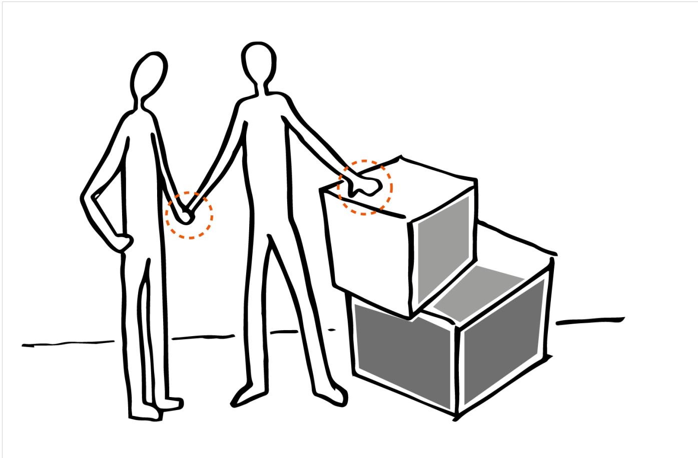

Fig. 2.1. The world as perceived by the haptic sense.

The role of touch is an essential component of embodied cognition. Psychologist James J. Gibson [6] has differentiated between two types of touch, such as active and passive touch. Active touch refers to the explorative procedures used by humans to scan objects with their hands, employing both cutaneous and kinesthetic senses. On the contrary, passive touch describe when a person is touched. The first reflects a voluntary control of humans over their sense of touch because an action is initiated by moving the body towards an object. Passive touch happens when there is no control over the sense of touch. Experimental evidence showed that a person identifies objects better while actively exploring their shapes, instead of when the objects were pressed against the hand [7].

Embodied cognition has attracted the attention of the field of Human-computer Interaction (HCI) and interaction design, by taking the form of an approach defined by Paul Dourish as *embodied interaction* [8]. For Dourish, embodiment represents a passage from the act of thinking (which had characterized the first wave of human-computer interaction) to the act of doing, which opens new possibilities of thinking our interactions with computational artifacts, and then propose a conceptual background for designing new interfaces. Despite the popularity that the idea of embodied interactions had in the last decade of HCI, this approach fails to consider the fundamental role of the coupling between perception and action in the experience of the world [9]. As noted by Gillspie and O'Modhrain [10], the perspective of embodied cognition challenges the notion of the interface at its root. By questioning the idea of an interface, embodied cognition questions some of the dominant paradigms in HCI. For instances, the HCI community has emphasized the notion of *transparency* of the interface. According to many researchers and designers, the best interface is the interface that disappears from the awareness of the user. By taking the perspective of embodied cognition, we can see that the relation between a human and a computer, and therefore with an interface, is not privileged, but it is just a component of the relations between a human and an environment that is computationally mediated. This relation coexists with other instances of interfaces between a person and an environment, like a person and a table, or the feet and the floor [11].

We can then realize that since cognition is extended, our thinking and awareness is distributed through the world of objects and materials, and its a process that emerges through such encounters. For instances, Malafouris [12] underlined that since ancient times, humans had used materials such as clay tablets to store complex process outside the brain. Also, that process of manipulating materials like clay gave the emergence to complex processes of cognition and intelligence, like performative and artistic. Moreover, recent theories of embodiment proposed to consider also the agency that materials and objects possess. Knappet [13] noticed that when an object is imbued by humans with a purpose (i.e. affective, or utilitarian) an object might act as an agent. If we look at the contemporary technological landscape, especially at personal assistants like Amazon Echo, or humanoid robots, we can clearly see how objects are redefining our environment through their agency. This poses new questions. When an objects shape and materiality are determined by digital processes, how these relate to humans? How can we interact and feel an object that can change its characteristics?

What happens to the "interface" when the computational artifact is not a tool used to execute a task, but it becomes an object that represents digital processes?

2.2 The World of Media

More than before, nowadays humans experience the world through the augmentation and facilitation provided by media, especially electronic and digital media which has become more and more pervasive. Even if the expression *media* has been used to describe a reality that is 'mediated' through technological artifacts, the meaning of media should be related to aspects of sensorial experiences. According to the original formulation of Marshall McLuhan [14] a media is "*any extension of ourselves (...) any new technology*" that affects the way how humans perceive and understand the world. This includes not only television, smartphones or radio, but also cars, typography, light bulbs, and ultimately language itself. Then, McLuhan underlined that the most important element of the media is not its content, but the mental, cognitive and social consequences created by the particular characteristics of the media itself. This is the meaning of his famous sentence: "*the medium is the message*" (Figure 2.2).

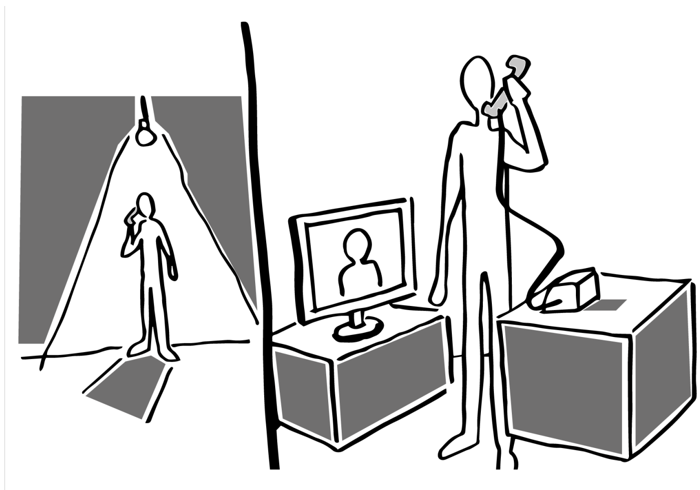

Fig. 2.2. The world as perceived and extended by media.

Moreover, McLuhan defines two ways in which humans relate to media and how much involvement is required for the user experience such media. For this, he developed the notions of "hot" and "cool" media. Hot media are technologies that do not require the full participation of the user since they already provide high sensory data. This includes radio, cinema, and photographs. On the other hand, cool media provide less sensory data and require more participation from humans, asking them to complete them with their imagination, memory, and interaction. This includes telecommunication technologies such as mobile phones, and television. However, this distinction is not qualitative, but pertains different types of experiences and engagement of a user with a media, and not to the cognitive effort required to experience and understand a particular media. As we can see, McLuhan has developed an analysis of the qualities of media through a haptic metaphor. Hot media can be considered too hot to be touched since they already provide many sensorial cues and information channels. Cool media can be touched (or completed) by users. This means that the friction generated by user interaction can warm them up. This distinction, even if it can be perceived as a simplification, provides a useful way to categorize and analyze any new media. In this thesis, we use the concept of "media" from this definition of McLuhan, to look at technologies not in their ability to deliver specific content, but on how such content can be experienced by possible users.

2.3 Virtual Worlds

One media that since the 1970s started to attract a lot of attention is Virtual Reality. However, Virtual Reality is usually defined as a technological system composed of: a computer for real-time rendering, controlled by a set of input devices with position tracking, and a head-mounted stereoscopic display. But, more specific definitions of VR went beyond such a limited description. For instances, artist and theorist Roy Ascott [15] defined Virtual Reality as a media that "*encompasses a whole ontology (...) of sensory immersion and immaterial connectivity, which affords the construc-*

tion of new worlds completely liberated from the constraints of mundane physics". Moreover, he points that such media "*changes the way we view ourselves, the manner of our comportation, and environments we wish to inhabit*". Therefore, we can say that the important characteristic of Virtual Reality is precisely its capability of producing sensorially rich environments, where the interaction between a user and a virtual world plays a fundamental role (Figure 2.3). For this, beyond any specific technology, the main goal of VR is the creation of a convincing sense of presence. Presence can be defined as the sense of being in an environment, which is determined by the process of sensorial stimulation and the interplay of perceptual and mental processes.

However, recent advancements in portable displays and powerful GPU processors have resulted in an increasing interest in Virtual Reality. Nowadays, VR research is not only characterized by universities and big corporations, but it has become inhabited by practitioners and designers from architecture, gaming, music, and medicine.

Fig. 2.3. A representation of the physical and the digital worlds. On the left, the physical world, as occupied by the human body. On the right, the virtual world as occupied by immaterial objects and avatars.

Most of the research in VR focuses on Computer Graphics, as a way to simulate and generate more convincing virtual worlds. This has resulted in a focus on visual display technologies, such as head-mounted displays, augmented environment such as the CAVE system, or spherical displays and even room-sized environments where not only a single user but a multitude can feel immersed [16]. Another important strand of research in VR has focused on developing devices to augment users and extend their sensorial capabilities for interacting with virtual realities (Figure 2.4). Especially, researchers in the field of haptics have been working to develop systems to facilitate the dynamical coupling between the human body and simulated environments. Such interfaces are mostly used to mediate touch through electro-mechanical systems, and used to support the execution of specific tasks [17].

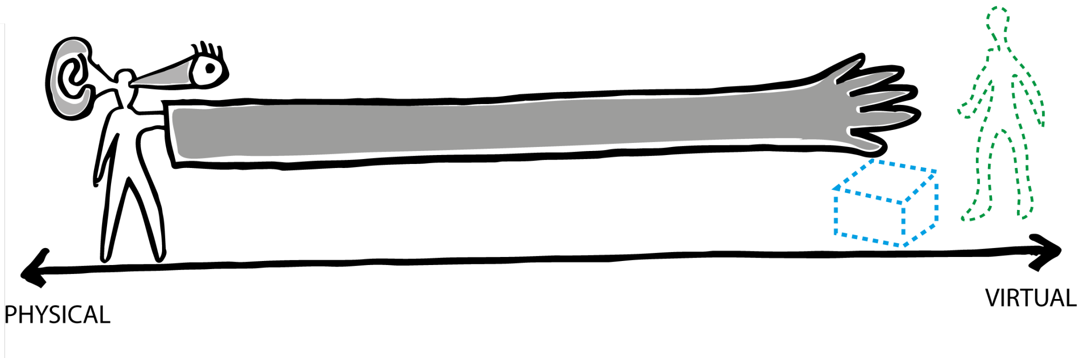

Fig. 2.4. To bridge the physical and the digital world, several extensions can be used. They can be visual, auditory, and tactile. The result is an augmentation of the human capabilities and the creation of new physical sensations produced by the encounter with virtual objects.

However, the idea of the display was extended by computer scientist Ivan Sutherland through its influential vision of the "Ultimate Display" [18]. In this article, Sutherland went beyond the idea of computer graphics or input devices, by envisioning that the ultimate frontier of virtual reality is a "*computer that controls the existence of matter*". Already in 1965, such idea showed that in order to create new and immersive experiences, is our material and physical reality that has to be enhanced with computation, and should capture our senses, or at least be experienceable in the same way used by humans to engage with their physical world.

While Virtual Reality systems try to recreate sensory experiences in the real world through a simulated experience, malleable media tries to represent information and virtual objects in the real world that users can directly and physically encounter.

2.4 The World of Data

Because of the widespread use of embedded sensor networks and mobile systems, digital data have penetrated our everyday lives, which has raised a new set of questions. Most of these questions pertain to the integration and engagement of data. Many questions are also related to the methods used for displaying data and making it comprehensible to humans. This is done by the visual representation of data present in the form of a sheet filled with numbers as histograms or charts. We can notice that in the common discourse there is a tendency to talk about data in a general and abstract manner. As ethnographer Dawn Nafus [19] noticed, we are witnessing the emergence of a tendency named as the *domestication of data*. With this expression, Nafus defines a process of consumption and adoption of data using widely available technologies such as personal computers or mobile phones. If in the recent past these technologies were originally designed for very specific applications, they quickly proliferated once people started of adopting them in their everyday lives. However, the concept of domestication of data does not refer to a process of making people data scientists, but to the development of new ways of using, sharing, and engaging with abstract data. This includes ways of representing them, and how data can generate and inform new social practices. As for representation, we can think of "data visualization" or "data journalism" which changed the way on how newspapers and websites present complex datasets to the public. The commonly used way to represent data is through numerical and waveform visualization techniques, and pixel-based displays are unable to depict the embodiment of data adequately and to intuitively represent data in forms easy for our consumption and comprehension [20].

The continuous production of information and communication of data is usually expressed through verbs such as *stream* and *flow*. It is very common to refer to processes such as *data streaming* and *information flow*. Such expressions evoke the image of the behavior of natural elements such as air and water, and it can also be extended to physiological processes like blood circulation and respiration. However, this flow cannot be physically perceived by humans. We cannot hold a stream of water; we can just feel it by inserting the hands into a torrent. Similarly, the flow of electrons or the waves of a Wi-Fi network cannot be physically grasped. The use of such expressions in daily life suggests that the next step in information society will involve us getting physically closer and connected to the unstoppable flow of digital information and data production.

2.5 Experiencing Virtual Worlds: Interactive Media Art

Along with the work done in the field such as engineering and HCI, in the context of media art several artists have explored conceptual and technical ways to create new interactions and relations between the virtual and physical world. Many of them have paid attention to the role of the human body and the feeling of touching or being touched by virtual objects plays a central role in the creation of new artistic experiences [21, 22].

A pioneer in the investigation of the relationship between the human body and virtual environments was the Australian artist Stelarc. Much of the production of Stelarc consists of exoskeletons and robotic prosthetics that can be either controlled by the artist himself (through EMG sensors) or can be controlled by users on the internet [23]. An example is a five-days performance "RE-WIRED / RE-MIXED: Event for Dismembered Body", where the body of the artist augmented with an ex-

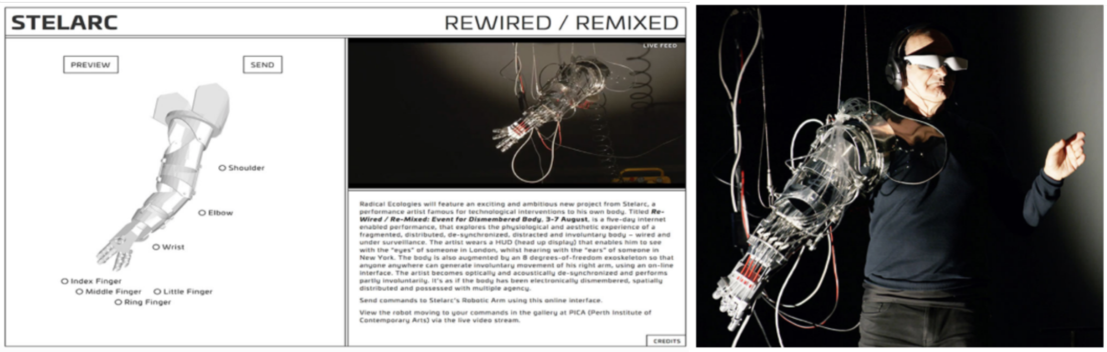

Fig. 2.5. Two images from the performance "RE-WIRED / RE-MIXED" by Stelarc. On the left, a web interface that can be used by remote users to control the body of the performer. On the right, the artist in the gallery space.

oskeleton, video headset, and noise-canceling headphones- can be controlled remotely by users through the internet[1]. In this way, the body became a fragmented, de-synchronized, spatially distributed, and expanding its agencies in different parts of the world (Figure 2.5).

Christa Sommerer and Laurent Mignonneau are two artists who had deeply engaged an investigation on how to connect human senses and digital processes by developing interactive artworks that have contributed in the creation of more physical and embodied interactions [24]. From there first work "Interactive Plant Growing" (Figure 2.6), where real plants were used as interfaces to control the growth of virtual plants. Each plant had a function (including also destring the simulation).

Another work of them, "A-Volve" was considered by many critics and theorists as a ground-breaking work in media art. A pool filled with water was used to display virtual creatures created by users through a touchscreen interface. Then each creature was released in the pool, and people can interact with them by waving their hands in the water. Users can either push the creatures in different directions or protect them

[1] `http://stelarc.org/?catID=20353`

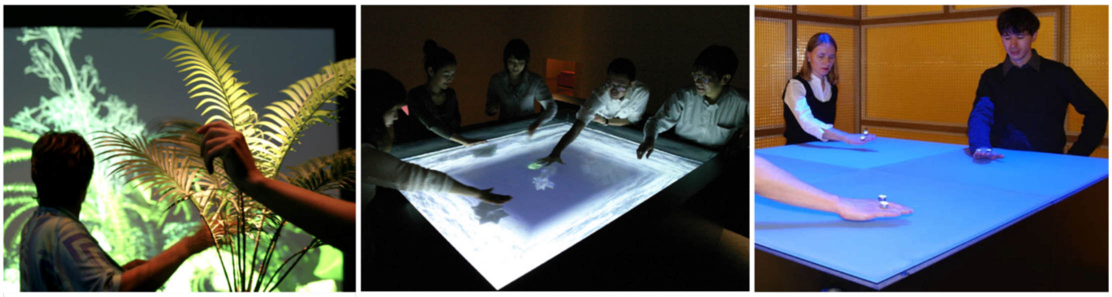

Fig. 2.6. Three works of Christa Sommerer and Laurent Mignonneau involving a physical interaction with virtual worlds: “Interactive Plant Growing” (left), “A-Volve” (center), “Nano-scape” (right).

from potentials predators. A genetic algorithm was controlling the behavior of the creatures which were interacting also between each other.

This type of work showed a form of direct interaction with the virtual world through as a relationship between humans and the virtual creatures they created. Similarly, Sommerer and Mignonneau have developed an installation “Nano-scape” where users by wearing a magnetic ring, can explore the shape of an invisible virtual sculpture, which was displayed through a force generated through an array of electromagnets.

Artist and computer graphics pioneer Yoichiro Kawaguchi proposed the concept of “Gemotion” as a way to realize a new form of *human art communication* [25]. Kawaguchi underlines the necessity for artists to develop new media that can support the sense of touch and physical involvement with an artwork, similarly to how we do it now with vision. He proposed the idea of a physical screen that communicates to viewers through physical motion. This must be synchronized with computer graphics. When a virtual creature is displayed visually, the screen will produce the behavior of such creature: if angry, the screen will move violently, if relaxed the screen will move softly (Figure 2.7). The concept of “Gemotion” shows that the next material for media artists will be physical materials that can be dynamic like computer graphics.

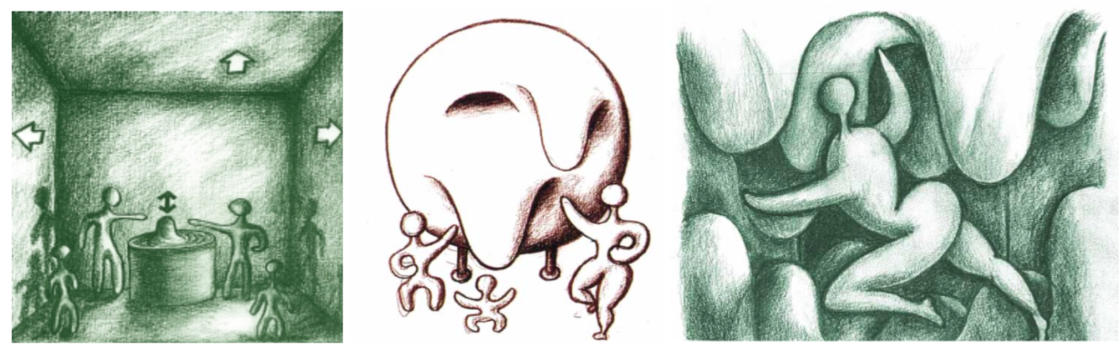

Fig. 2.7. Three sketches by Yoichiro Kawaguchi that illustrate the concept of “Gemotion”.

If engineers and computer scientists have contributed to the development of new mechanisms and infostructures, artists have formulated conceptual tools for envisioning future scenarios and try to anticipate social issues generated by new virtual reality technologies. Also, media artists have explored new aesthetics and new types of experiences that can be generated through emerging technologies. From this point of view, media art can be seen as a platform for interdisciplinary research by involving not only the artist himself but also a wide range of experts in robotics, artificial intelligence, music, biology, and even surgery. One example is the Device Art movement, which has shown how new technologies can be used to deliver new aesthetics experiences, through a collaboration between artists, theorists, and engineers [26].

2.6 The World of Dynamic Materials: Shape-changing Interfaces

Since the last decade, several designers and researchers have explored materials that use changes in their physical properties to provide new ways of interacting with digital processes. Shape-changing materials can be defined as materials that undergo a mechanical deformation under the influence of direct or indirect stimuli. From this explorations, a new research area has emerged in the field of HCI, and then defined as shape-changing interfaces. Shape-changing interfaces have been defined by Alexander et al. [27] as interfaces that a) use changes of shape or in materiality as input and output; b) are either computationally controlled or interactive; c) are either self-actuated or directly deformed by users; d) can convey meaning, information, or affect to users. Shape-changing interfaces are currently an emerging research field, composed mostly by prototypes which range from different applications and form factors like deformable smartphones, to physical displays, and even swarm of drones that can self-assemble to represent UI physically (Figure 2.8).

Fig. 2.8. Three examples of shape-changing interfaces: "Project FEELEX" [28] (left), "Materiable" [29] (center), and "Griddrones" [30] (right).

One of the early conceptualization of this idea, and review of its design space was done by Poupyrev et al. in 2007 [31], but mostly focusing visual displays and actuated tangible user interfaces. After, Coelho and Zigelbaum [32] proposed to define shape-changing interfaces by relating them to the advances in material science especially on "smart materials", which can open new interactions and metaphors. A 2012 review by Rasmussen et al. [33] provided a broad overview of the existing body of work on shape-changing interfaces, and proposed a classification based on the types of transformations, and interaction. Recently, Sturdee and Alexander [34], looked at the deformable qualities of shape-changing interfaces and their characteristics as displays with collocated visual and physical output. Then, Alexander et al. [27] identified the main characteristics of shape-changing interfaces as an emerging research field in HCI and proposing a research agenda.

As we showed early, the idea of controlling physical properties of interfaces as a way to create new interactions and represents virtual objects dates back on the proposal of the "Ultimate Display" of Sutherland. Even though such an idea has influenced the initial development of virtual reality interfaces, it then expanded through different proposals of using robotic systems to make digital content physical. This resurgent interest in the more radical proposition of Sutherland can be seen reflected in concepts such as "Programmable Matter" [35], "Digital Clay" [36], "ClayTronics" [37], or more recently with the idea of "Radical Atoms" [38]. As we saw before, also a concept like the one of "Gemotion", showed how media artists have embraced this idea. Despite some difference existing between such ideas, they all point towards a direction where physical computational artifacts will have with the ability to take any shape and dynamically reconfigure themselves, and by doing so, these new types of devices will be perceived as a new type of material, that is controlled by computational processes. Such visions led to the exploration of different techniques such as dynamic surfaces that can add haptic sensations to computer graphics [28], or render physical and dynamic affordances [29,39]. Researchers have also explored ways to use swarms of flying robots that can spatially re-arrange to create different shapes [30], and even by adapting techniques mutated from chemistry and synthetic biology as a way to create dynamic physical objects [40].

However, such research field is still in its initial stage, and there are many open challenges, especially technical ones. One of the open technical challenges is the creation of interfaces that can represent arbitrary 3D shapes and materials that can change their physical characteristics on demand. Another issue connected to the development of mechanisms to control the materiality and physical appearance of surfaces is the perception of such changes, which at the moment have not been studied deeply. This is a very important issue to address. We must ensure that the human haptic systems correctly perceive such systems since they have been mostly explored visually. In the present study, we will outline several methods to investigate the haptic perception and social impact of shape-changing materials.

2.7 The World of Interconnected Devices: Internet of Things

The Internet of Things (IoT) refers to an emerging type of scenario, where internet connectivity is extended to everyday objects, such as home appliances or vehicles. When augmented by computation and internet connection such objects allow direct interaction with humans through a variety of input and output modalities and mostly can exchange data through the internet. Entrepreneur David Rose proposed the look at IoT devices as *enchanted objects*, to shift the attention from the pure technological aspect, to the fundamental characteristic and impact that such devices will have humans life [41]. In Roses vision, interconnected and ambient-aware devices will compose the background of our environment and will enhance human capabilities, communication, awareness, and even expression. Recently, several devices appeared on the market, such as Amazon Alexa, Google Home, RoBoHoN, Ori Pocket Closet. However, such devices still do not exploit the haptic channel of communication, being mostly voice-based systems. This thesis aims to extend the use of malleable media in the context of IoT to present data through computationally controlled materials. Also, they usually use voice commands as interaction, while not exploiting the haptic channel. Differently, from Virtual Reality, the IoT is creating enchanted objects that blend digital reality with the real one. While VR is making experiences more real, IoT expands by controlling physical objects through digital processes and interconnected experiences. The proliferation of IoT devices poses a question, about the role of objects that possess agency.

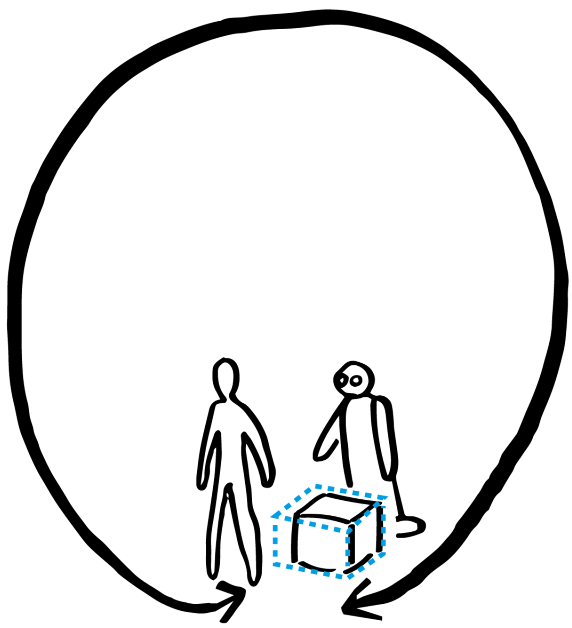

Fig. 2.9. The current techno-social landscape. Differently from what was envisioned by VR researchers, the appearance of technologies such as shape-changing materials, IoT, and robotics has caused the physical and the virtual world to converge.

2.8 The Convergence of the Virtual and the Physical

Through this chapter, we showed how most of the research in engineering and computer science has tried to make virtual experiences feeling more real, through the use of computer graphics, and physical through various input devices and haptic interfaces. Also, we looked at how media artists have tried to explore new concepts of interactions with virtual worlds. However, the current technological landscape shows that thanks to several advancements in shape-changing materials, IoT, and intelligent robotics, the way how we experience our physical reality is becoming more virtual. More virtual in the sense that our materiality is taking and showing the type of malleability that characterizes the digital world at large, through shape-changing materials that like computer graphics are changing the size and physical properties, and like digital data are evolving in real-time. This causes the space between our physical reality and virtual realities to wrap and making contact between these two extremes. However, this is not caused by the creation of instruments and tools, but because our physical reality and the objects around us are becoming more and more imbued with digital processes which can determine their appearance and functions (Figure 2.9). We position the research proposed in this thesis inside this wrapped space between the physical and the virtual.

3. RELATED WORK

The works presented in this thesis is positioned in the intersections of several lines of research, such as data sculptures, haptic interfaces, and technologies for shape-change. In this chapter, we will review the main related work and discuss the main differences between our research and previous studies.

3.1 Data Sculptures

Recent innovations in low-cost fabrication and embedded computing have sparked a new interest in how physical artifacts can present and integrate digital information in our environment. Along with techniques such as data visualization and sonification, Jansen et al. [42] have proposed data *physicalization*. Data physicalization is a way of encoding abstract data into material properties and using the inherent capabilities of objects to communicate meaning and functionality using the natural affordances they possess. This can lead to alternative representation media that learn from humans experiences and interpret the world around them. However, physical representations of abstract data have been developed by humans for centuries. Such a way of representing information also played a role in shaping the horizons of science and culture in the last century. Let us look back at the molecular models of Penicillin created by Dorothy Crowfoot Hodgkin in 1945, or the physical model of myoglobin developed in 1958 by Kendrew and colleagues. Such physicalizations enabled a better understanding of complex data sets and gave spatial representation to elements such as molecules. Data physicalization offers a multitude of potential benefits over its purely visual and sonic counterparts [43]. Firstly, general data encoded in the material qualities of a physical object can be directly manipulated. Such characteristics are very different from those of ambient displays, which are mostly based on ephemeral elements (such as light and air) and are mostly designed as peripheral devices. Secondly, the physical modality can offer a wider range of new possibilities for interaction compared to on-screen visualizations, since physicalizations require active engagement from the user. If ambient displays are good at showing changes of data over time, data physicalizations can better embody information in objects that can be grabbed and actively explored by users. Thirdly, data physicalizations can be integrated within the life and environment of users, allowing the presentation of abstract information in a more direct, complex and even pleasurable way compared to other types of media used for information presentation [44].

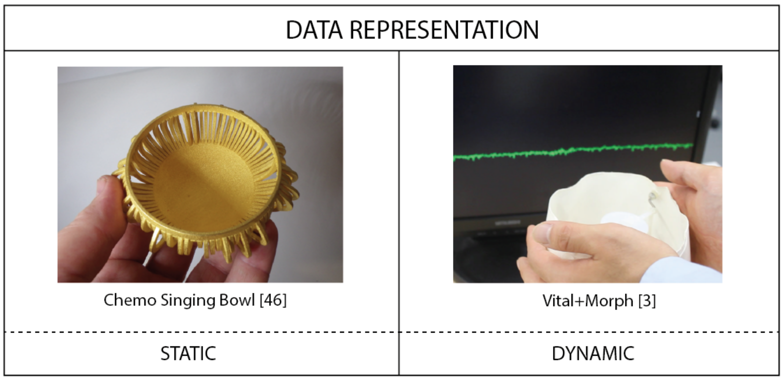

Fig. 3.1. Physicalization of biomedical data through data sculptures and malleable media. On the left, a static representation of blood pressure value through the “Chemo Singing Bowl”. On the right, blood pressure as represented by “Vital+Morph”, which is dynamic.

Data physicalizations can also have an artistic purpose. Digital data has rapidly become a new material used by artists to investigate the contemporary landscape. This trend was exemplified by the term information aesthetics [45], which describes visually pleasing artifacts that communicate information. An interesting example of information aesthetics is a data sculpture [20], which is a direct representation of data in a physical form with its only function being to convey the most suitable meaning to viewers. However, the data mapping metaphor employed in data sculptures may not be immediately understandable and forces viewers to reflect on the process and on how data is embodied in a physical form. Moreover, viewers must interpret these data-driven objects by the affordances the objects convey. Information translated into physical artifacts can be grabbed, touched, and carried like souvenirs or jewelry. An interesting example of a data sculptures is the “Chemo Singing Bowl” [46]. This is a 3D-printed sounding sculpture which embodies the data of blood pressure recorded over a period of one year from a patient who underwent chemotherapy for breast cancer.

While data sculptures and other types of physicalization have been proved to be useful and attractive, they must be designed and fabricated in advance, and modifications of their physical characteristics are often limited once created. We propose shape-change as a way to encode data into objects properties in real-time and in a dynamic way. This can increase the agency and the embodiment of the data-driven objects and communicate to users by using time, which can be following the progression of the data as similar to looking at a graph forming on a screen for example while monitoring heart-beat on a wearable monitor. Adding dynamic shape-change to data sculpture enables them to be connected to the internet and display data in real-time (Figure 3.1). In addition, most of the research on data physicalization has focused on understanding the visual perception of data sculptures [47]. We propose through this work to focus on the haptic perception, being the most important channel of communication of data physicalizations. Combining passive touch with haptic feedback in the form of force feedback.

3.2 Shape-changing and Dynamic Data Physicalizations

Information delivery is one of the key use of shape-changing interfaces, and dynamic data physicalization can be considered as one of its most compelling applications. Differently from data sculptures, the use of shape-changing interfaces add the component of time to data physicalization. However, most of the current dynamic physicalizations make use of widely used visual metaphors borrowed from data visualization such as pie charts and animated bar charts [48–51]. These shape-changing interfaces support the translation of pixel-based data by translating the change in a pixels value into corresponding changes in height. This is only one of the many possibilities that can be explored, such as the mapping of data to physical variables of materials such as smoothness or hardness all of which provide additional feedback and methods for data physicalization.

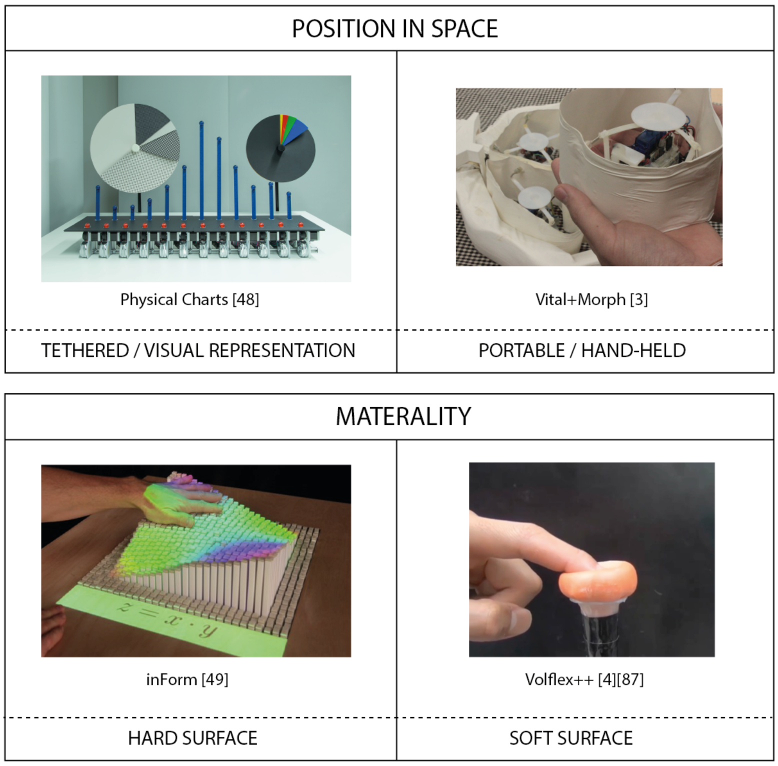

Fig. 3.2. Dynamic data physicalization through current shape-changing interfaces, which are tethered and rigid, while malleable media are portable and soft.

The works presented in this thesis add to the current research on shape-changing interfaces for data physicalization a strong focus on haptic interaction (Figure 3.2). In most cases, the user does not have to interact directly with the physicalization. In the work of Taher et al. [51] the user controls a group of actuated bars through a touch-screen interface. In the case of inForm [49] and Relief [39], the interaction is mostly gestural, which does not require any direct contact with the surface. Through "Vital+Morph" and "Volflex++", we explore the role of passive touch for the perception of changes in data through shape-change and the role of active touch for understanding surface elements such as size and rigidity.

Even if researchers in data physicalization have underlined the importance of intermodal perception, the only visual perception was studied. This resulted in a lack of understanding of other perceptual modalities, such as haptic. As underlined by Alexander et al. [27], the role of the haptic perception is not yet fully understand in the context of shape-changing interfaces. This is an open issue in research. Understanding the haptic perception of the changes of shape and materiality represents a fundamental element for understanding both the tactile resolution of such interfaces and understand how users perceive data physicalization.

This tendency of considering shape-changing interfaces as a physical display has turned in attention on resolution, as visual quality [34, 52]. For instances, the design space developed by Rasmussen et al. [33] outlined several types of changes using a vocabulary borrowed from visual perception (Figure 3.3), like the notion of *viscosity*. In the context of this research, we will use the notion of *rigidity* that is more related to the tactile perception of materials. Jansen and Hornbaeck [47] developed a psychophysical study of user perception of changes in size but only in terms of visual perception. Our work adds a psychophysical study on the perception of the changes in size through the haptic channel.

The current focus on the visual resolution has generated prototypes that are similar to visual displays, (such as screens and monitors) which are immovable, and can be perceived only through vision. This is also connected to the type of actuation technology used in most of the current prototypes. Systems like the one proposed by Nakagaki et al. [29] and [51] present an adequate resolution in terms of density of the motorized pins. However, larger arrays of linear actuators require power and cabling to transfer the motion to the pins of the surface. Therefore, such interfaces cannot be manipulated and held by users. While tethered shape-changing interfaces are also

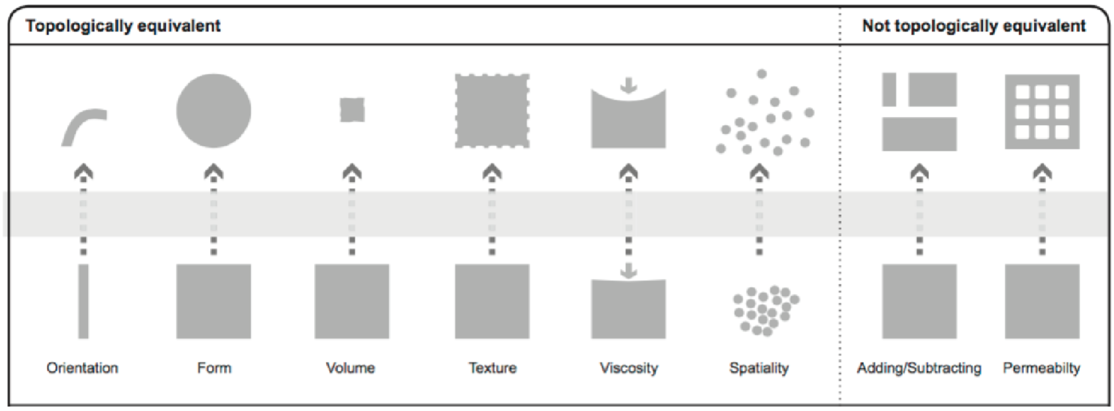

Fig. 3.3. A representation of different types of shape-change by Rasmussen et al. [33]

explored in this thesis, with "Vital+Morph" we propose a method to design portable shape-changing interfaces with embedded actuators, characterized by low-power consumption, and designed as IoT devices.

Another substantial difference between previous work on shape-changing interfaces and data sculptures is the use of materials. Rigid materials compose current prototypes. In contrast, in this thesis, we explore deformable materials, which can let users to physically deform the shape of the object, which cannot be achieved with rigid surfaces. We also explore hybrid materials with the ability to alter their rigidity depending on the type of data they need to represent. In the context of malleable media, we look at both direct deformations as provoked by user's action, and deformations as provoked by self-actuation of the system. Also, in shape-changing interfaces, only general datasets have been explored. In this thesis, we propose to look at biometric data, as an example of a very specific and sensitive type data. We believe that testing specific data sets will help to understand what dynamic physicalizations can be successfully used.

Lastly, most of the evaluation of shape-changing interfaces performed until now did not provide sufficient information on the possible social impact of shape-changing materials and data physicalization. In this thesis, we propose a method for the evaluation of shape-changing interfaces through the creation of a media art installation that narrates a specific scenario.

3.3 Haptic Interfaces

Haptics is a large research field, which includes both the study of human perception and the design of technologies capable of making virtual objects and materials perceivable by human touch. In this section we will review the latter, and focus on what is usually referred as "haptic interfaces" [17,53]. Haptic interfaces can be divided into three main categories, such as exoskeleton-type, tool-type, and encountered-type. We will refer to these types in relation to the contributions provided by this thesis (Figure 3.4).

3.3.1 Exoskeleton-type

Exoskeleton-type haptic interfaces are composed of a series of actuators attached to the users body. Such haptic interfaces are mostly used in robotics as master manipulators or as a way to enhance and augment human movements and force. Iwata [54] developed one of the first examples of exoskeleton-type haptic interfaces, which provide high flexibility and degrees of freedom. Recently, lightweight and low-cost portable exoskeletons have also been developed especially for the interaction with virtual objects and augmenting users with physical impairments [55, 56].

3.3.2 Tool-type

With tool-type haptic interfaces, the user grabs an endpoint usually in the shape of a pen or joystick [57]. These are probably the most common haptic interfaces, used in

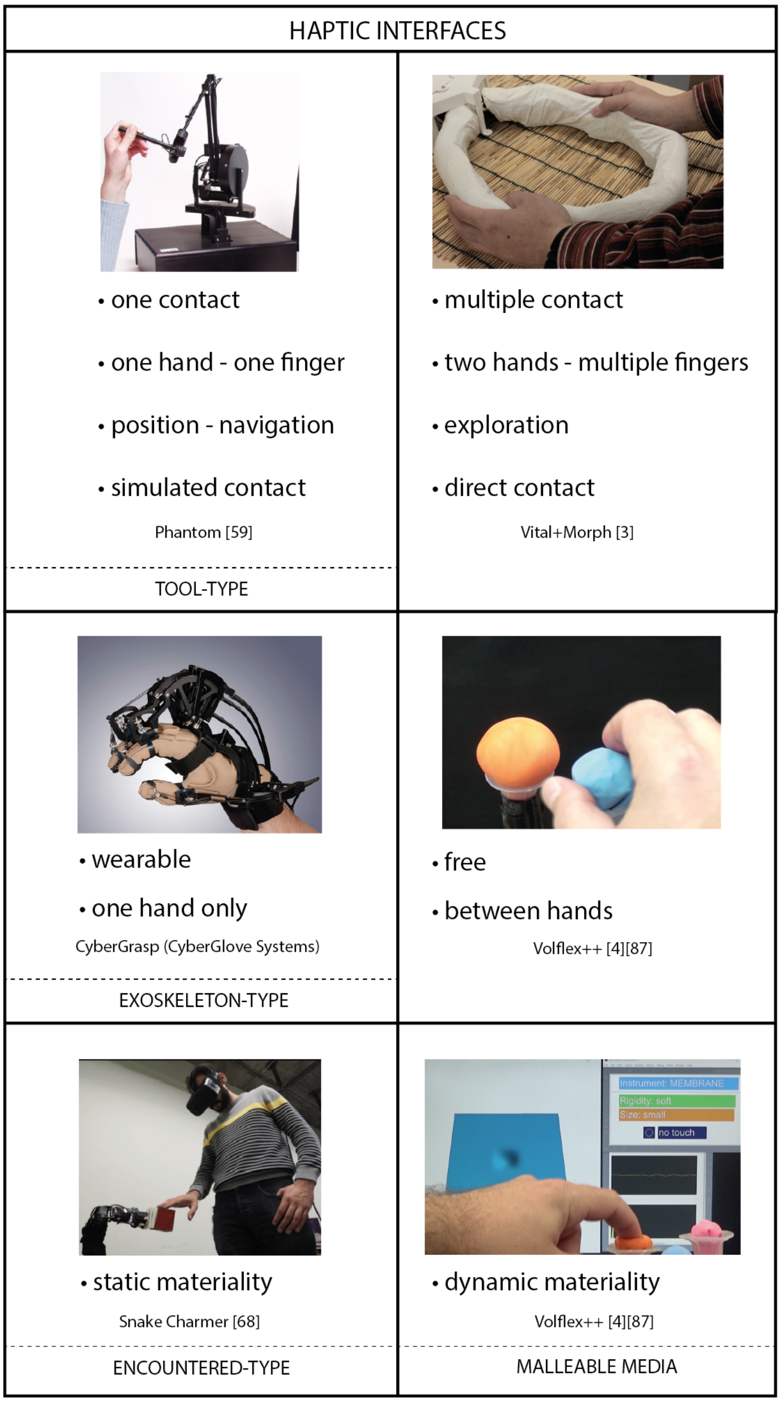

Fig. 3.4. A summary of the main differences between haptic interfaces and the two case studies presented in this thesis.

a variety of fields like medical, product design, and video games. Two main examples are the Haptic Master [58], which is a grip supported by a 3DOF pantograph that enables complex types of kinaesthetic feedback. The PHANToM [59] used a similar approach, which rapidly became one of the most popular commercial haptic interface for its simple design, low-cost, and portability.

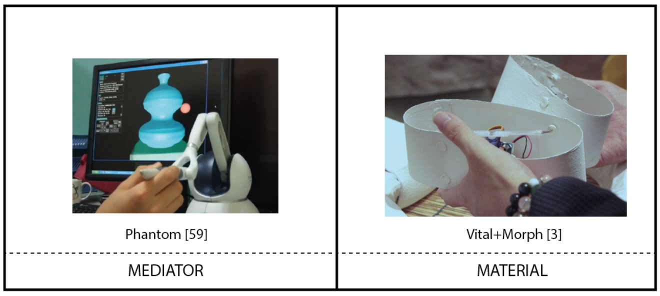

Fig. 3.5. A summary of the main differences between haptic interfaces and the two case studies presented in this thesis.

Mostly, tool-based haptic interfaces are used to support the execution of a task, such as navigating, probing, selection. Because of their explorative nature and use for communication, the works presented in this thesis have to be considered prototypes of shape-changing materials. Like materials, they do not possess a specific function, but they can generate tasks, and amplify or directing the meaning of an object. Another significant difference with exoskeleton-type haptic interfaces is that the system we present do not constrict movement since they do not require users to wear any additional mechanism. Thus, users can use their hands -and potentially any part of their body- to interact with virtual objects as we do with objects in the physical world. Both exoskeleton type and tool-handling type interfaces render touch sensations only through limited contact points and therefore do not fully support active touch and limit explorative procedures. While hand exoskeletons can excel in grasping, fail in contour following, while tool-handling can render details of a surface. Both cannot be used with two hands, and it will need a device for each hand or even fingers. Moreover, this type of haptic interfaces is used to mediate touch through electro-mechanical systems. However, in our daily life, we encounter surfaces directly, and we explore them not only with the fingertip but the whole hand and explore them by moving the hands on the surface. Such limitations have led to the emergence of a third type of haptic interfaces which tries to re-establish such interaction between humans and objects in the same space.

3.3.3 Encountered-type

Encountered-type of haptic interfaces represents an alternative approach to the ones described before. These haptic interfaces aim to facilitate direct contact between a user and a virtual object. In an Encounter-type haptic system is the interface that moves or deforms itself to simulate the shape and the characteristics of a virtual object. This approach focuses on rendering a virtual object (or some of its characteristics) in the physical world, rather than just force-feedback [60–62]. Examples of encountered-type haptics are robotic systems with a reconfigurable hand point that approximates the shape and geometry of a virtual object that can be directly touched and explored by users. These resulted in a high sense of realism and immersion [63,64].

Along with such major approaches, there are other types of haptic interfaces, like tactile displays that are used to render 2D textures to the user's fingertips. However, they cannot reproduce three-dimensional sensations and produce a consistent amount of force. Passive props have also been explored. Such elements do not require actuators, but they are just input devices, with sensors both external and internal that capture users touch and manipulation. This approach gained much attention with the idea of Tangible User Interfaces [65], where physical objects are used as a surrogate of GUI elements such as icons and folders. Research in VR sowed that using physical props that represent the objects placed in a physical environment can increase the sense of presence [66, 67]. However, being without actuators, such interfaces cannot be used to present arbitrary virtual objects, and need to be fabricated. However, they show that haptic interaction is essential both with force feedback and just with direct manipulation (Figure).

We position the works presented in this thesis in the spectrum of encountered-type haptic interfaces, since they can allow direct contact with a physical surface, can accept bimanual input and are spatially distributed. However, there is a main difference between examples of encountered-type haptic interfaces and the two examples presented in this work. Most of these interfaces have endpoints composed only of a specific material. This limits the type of virtual objects that can be presented and thus experienced by users. Even though there have been several examples of reconfigurable endpoints [68,69] these cannot change their materiality. We propose to extend such kind of interfaces by having surfaces that can present different types of material properties.

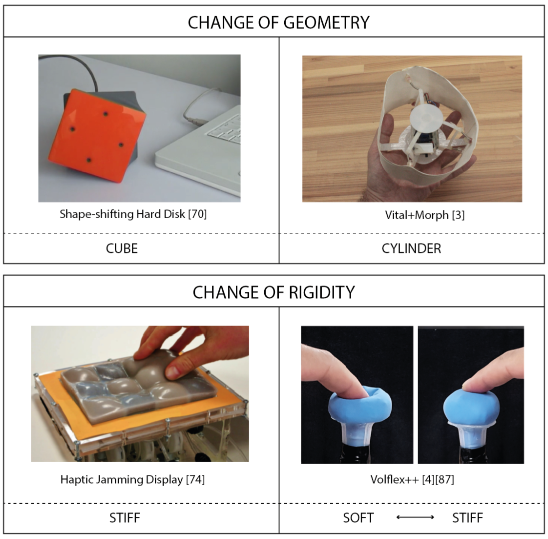

Fig. 3.6. The different types of shape-change possible with Vital+Morph and Volflex++, in contrast with the ones proposed by previous works.

3.4 Technologies for Shape-change

One element that characterizes the works presented in this thesis is the technological challenge related to the implementation of shape-changing interfaces. The main open challenge is related to the creation of interfaces that can represent arbitrary 3d shapes and materials that can represent arbitrary types of data. We look especially at the changes in geometry, size, and rigidity (Figure 3.7).

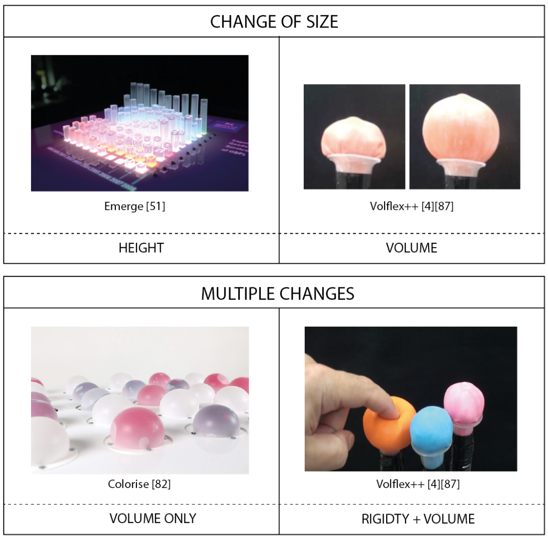

Fig. 3.7. The different types of shape-change possible with Vital+Morph and Volflex++, in contrast with the ones proposed by previous works.

3.4.1 Changes of geometry

A change in geometry can be identified in physical transformations that preserve the volume of the interface while changing the overall geometry of its shape [70, 71]. Such type of change has been explored by Hemmert et al. [72], through a series of mock-up shape-changing smartphones that can change geometry by using a set of embedded actuators. Through Vital+Morph, we extend such approach by considering not cubical shapes, but cylindrical, and not using rigid materials, but deformable and flexible materials, and extend the use of embedded and small actuators with a focus on producing haptic feedback.

3.4.2 Changes of size and volume

Changes of size maintain the overall geometry but alter one or more dimension of the surface. One of the most explored ones is the vertical change of size. FEELEX [28], Lumen [31], and inForm [49] are there prominent examples of shape-changing interfaces that can present arbitrary uneven surfaces through an array of linear actuators. However, their ability to change size is only in height, make them able to create only 2.5D objects, that emerges like reliefs. In this thesis, we propose a mechanism to change size in a volumetric way through the use of inflatable balloons.

3.4.3 Changes of rigidity

To achieve controllable rigidity, several shape-changing interfaces have explored the use of particle jamming. Through this technique materials properties can be changed between flexible and stiff states. ClayTric Surface [73] provides a surface that can be directly deformed by users and than then freeze it to capture the shape. Haptic Jamming [74, 75] provides a more sophisticated display composed of a group of silicone cells filled with coffee grounds. By vacuuming the inside of each cell the stiffness can be changed. Size can also be altered but only through vertical displacement. Particle jamming is useful for plastic deformations, while inflatable balloons for elastic deformations. Even if such systems can present uneven surfaces with variable stiffness, they cannot be used to display volumetric virtual objects and fail in producing soft materials. In this thesis, we propose a mechanism to control the rigidity through computer-controlled balloons.

4. METHODS

This chapter introduces the principal methodologies used in this thesis. Because of the interdisciplinary nature of our research, we have drawn methods from different fields, such as design, studies on haptic perception, and techniques for building shape-changing interfaces. We also introduce a method for evaluating novel technologies as media art installation.

4.1 Bio-inspired Design

Nature uses changes of shape in several forms. Especially living organisms to communicate and interact with the environment: flowers bloom to attract insects or alter their orientation to transform sunlight and heat into nutrients. Looking at nature to inspire new technological developments has been named as "Biomimicry" or "Bionics". Through these terms, we define a multidisciplinary approach that uses biological principles to designs in several domains such as informatics, medicine, art, robotics, and architecture (Figure 4.1). This approach can be traced back to the ground-breaking work of D'Arcy Wentworth Thompson "On Growth and Form" [76]. In this book, Thompson illustrates the existing correlations between biological and mechanical forms. He noticed that changes in rate, proportions and whole physical configurations are some of the most complex phenomena of the evolution of humans and living organisms in general. Additionally, Thompson found that the form of an organism and its evolution is an event that happens in space and time. The aspect of time and its relations with shape-change thus becomes very important.

During the 20th century several architects and engineers, such as Antoni Gaudi, Buckminster Fuller, and Frei Otto tried to expand the work of Thompson to derive new models of construction by looking at the "*physical, biological, and technical pro-*

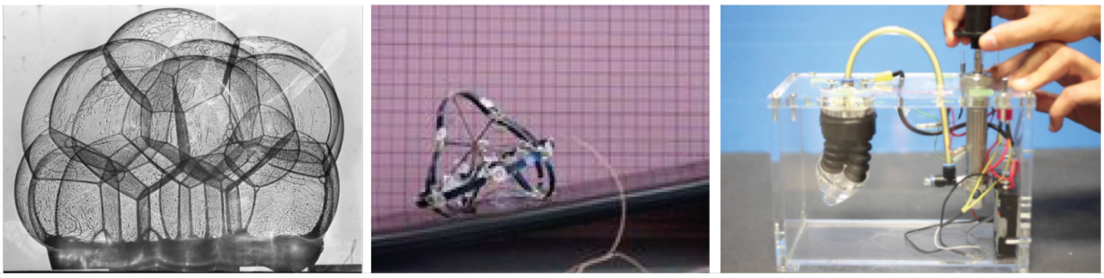

Fig. 4.1. Three examples of bio-inspired design. On the left, the studies of bubbles by Frei Otto for form-finding [77]. In the center, a jumping robot developed by [78], inspired by rheological materials. On the right, the “Plantoid” soft robot, which mimics the functions and behaviors of plants’ roots [79].

cesses which give rise to objects” [77]. In 1997, Jenaine Benyus [80] tried to identify Biomimicry as a research field. According to Benyus, we can identify three main levels of bio-inspired design. First by mimicking the shape or the external characteristics of a natural form, for deriving more sustainable design. Second, by mimicking natural processes in order to manage complexity. Third, by mimicking the entire natural ecosystem, since like in nature, an object of design will be part of a more extensive system of relations. Moreover, a bio-inspired design consists of an indirect approach to solve human design challenges. Recently, bio-inspired approaches became relevant in the field of soft robotics, for designing soft and deformable mechanics (deformable actuators review, soft robotics review). Several works involve the design and implementation of simple robots that can deform and adapt themselves to the changing conditions of the environment [78, 79]. Getting inspiration from nature to design shape-changing interfaces can open new possibilities for presenting digital data physically. As already noted, most of the current prototypes use representations from visualization, like pie and bar charts. A bio-inspired approach can be used to deal with the complexity of data sets and design more straightforward and compelling mechanical systems for controlling deformable objects. In this thesis, we used a bio-inspired approach to design the mechanisms and appearance of the two systems. "Vital+Morph" look at the shape and functions of diatoms, while "Volflex++" look at pneus.

4.2 Computationally Controlled Balloons for Shape-change

One of the open issues in the research on shape-changing interfaces is the identification of enabling technologies. Even though pin-based interfaces based on linear actuators have gained a great interest especially in the HCI community, other mechanisms and technologies have been proposed. One of them is composed by computer-controlled inflatable balloons, which is explored in this thesis. Inflatable balloons can provide a change of their entire volume [81,82]. Single balloons can be used to present different sizes of virtual objects by varying their internal pressure [83]. Combined in together, an array of balloons can be used to approximate volumetric shapes that can be actively deformed by users [84].

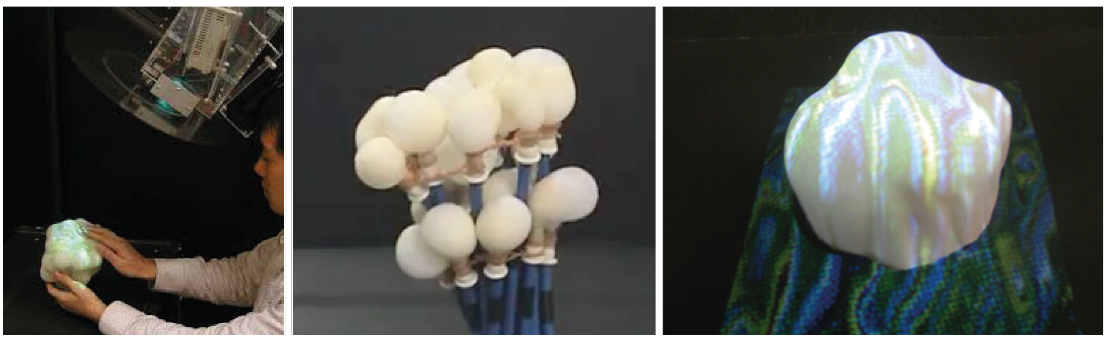

Fig. 4.2. The Volflex system. On the right, the first version, equipped with a special projector unit. On the center, a lattice of balloons. On the left, an image of the Volflex+ system.

4.2.1 Volflex Technology

Aside from such instances, one example of the use of computer-controlled inflatable balloons for building haptic and volumetric interfaces is the Volflex technology (Figure 4.2). The basic concept and mechanism of the Volflex technology were first introduced by Iwata et al. [84] in 2005. The aim of such technology is the creation of 'digital clay' systems that can display physically volumetric and three-dimensional virtual objects, and present visual and haptic sensations simultaneously. An array of computer-controlled balloons displays the resulting surface. The volume of each balloon is controlled through an air cylinder, whose position is controlled through a linear actuator. Each air cylinder is equipped with a pressure sensor used to detect the force applied by the user. Through this configuration, deformations of the surface will occur according to the hardness of the virtual object and material. However, unlike real deformable materials, it can be possible to either memorize or reverse deformations. Together with the haptic interface, the Volflex system integrates a system for creating co-located visual feedback. The system is composed of a projection and a video camera. The camera captures the users hand and removes the current background. The projector is equipped with a mechanical rotary shutter that separates the projector and camera. Through this technique, images can be projected on the surface that appears to be placed below the hands, and not on the top.

After the first proposal, the Volflex technology went through a series of implementations oriented to develop further several of its aspects. Abe et al. [85] proposed a new version of the device by arranging the balloon as a cubic array. To improve the passive haptic feedback, the pipes where the balloons are attached have been connected through springs, so that even if moved, the balloons can maintain their relative position. Through Volflex+ Enzaki et al. [86] introduced a hybrid mechanism that combines the Volflex technology with the pin-array like systems such as FEELEX. Each cylinder is attached to a linear actuator so that each balloon can move vertically upwards and downwards. This can create surfaces that expand from flat to volumetric.

These works have expanded the possibilities of Volflex to create a more convincing way to present virtual objects physically and interact with them. However, there is still an open issue since it is not possible to control the volume and the rigidity of each balloon separately. To create a rigid surface, the pressure inside the balloon has to be increased resulting also in a larger volume. To solve this problem Takizawa et al. [87] introduced two new mechanisms to control both size and rigidity of a single balloon. This is possible through the introduction of a non-expandable balloon, which allows more detailed control of the internal pressure. They further integrate also a position control system. To move the balloons vertically, the same mechanism of Volflex+ is used. To move the balloons in space a rotation and bending mechanisms are introduced. With the former, each balloon can be rotated on its vertical axis. With the latter, each balloon can be bend upwards and downwards. We based our research on this last implementation. The work presented in Chapter 6 is based on this last implementation of the Volflex technology.

4.3 Haptic Perception of Objects and Materials

The study of the human perception of physical properties of objects have been of great interests for the haptics community [88, 89]. Especially, the perception of material properties such as softness and stiffness have been studied quite extensively [90–93].

In order to discriminate the compliance of an object by tactile exploration, humans use their fingers to squeeze or indent their surfaces. Through these tasks, humans can gather information about the mechanical properties of materials and objects. In this study, we refer to properties like stiffness and softness as rigidity, as a more generalized way to describe the amount of physical deformation of an object for the amount of pressure applied (Figure 4.3). Haptic perception of size have been also studied [94,95]

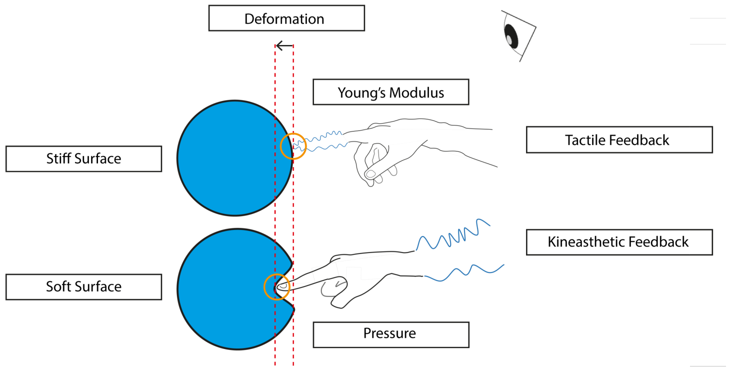

Fig. 4.3. A graphical representation on how humans perceive stiff and soft materials though the sense of touch.

through the use of different exploratory procedures (Figure 4.4), such as finger-span (e.g. [96]) or hand enclosure (e.g. [97]). Perception of size and rigidity are usually studied through psychophysical experiments. Psychophysics refers to a wide range of methods used to investigate human sensations and perception in relationship with physical stimuli. In this thesis, we propose to use psychophysics to study the human haptic perception of shape-changing interfaces. We conducted a study involving 20 participants to understand the human-factors related to the change of size and rigidity using the Voflex++ system. To measure the sensory thresholds, we used an adaptive technique known as the staircase method or simple up-down procedure [98]. Adaptive techniques have been suggested as an efficient way of estimating thresholds in haptics research [99, 100]. The threshold is estimated by adapting the intensity of a stimulus based on preceding stimuli and responses. Adaptive techniques can offer several advantages for haptic research. Compared to classical psychophysical, such as the method of constant stimuli, it is not required to plot a complete psychometric function since a simple up-down technique can estimate the 50% of the function. This reduces the number of trials, making the procedure more efficient, which helps to avoid physical and mental fatigue, which can impact negatively in the experiment. The procedure is adapted to the subjects, by making it harder or easier depending on their performance. Previous studies on perception of size and rigidity made use or of simulated stimuli using impedance-type haptic interfaces, or through several specimens fabricated with different materials and shapes. Differently, from previous work, our study is based on a a device that can present different rigidities and sizes on a single surface, that can be altered by a computer program.

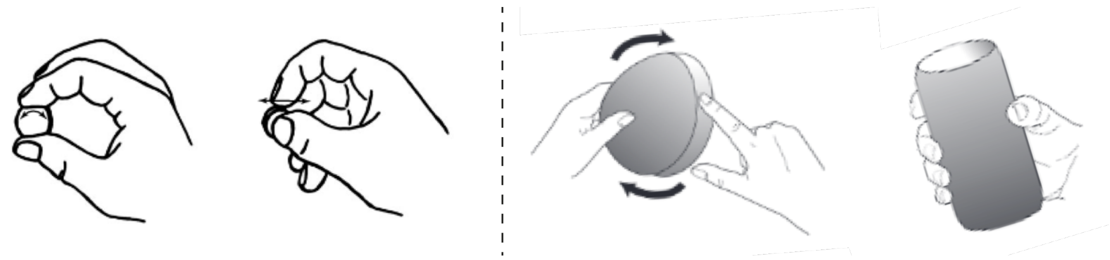

Fig. 4.4. How hands' movements can be used to gather information regarding the size of objects: through manipulation and rotation (left), or through contour-following and enclosure (right). These representations are taken from [94] and [7] respectively.

Hayward noticed that "display technologies may be thought to mirror the perceptual system of an observer" [94]. Therefore, the knowledge of perceptual cues, such as geometry, size, and rigidity, are useful to design systems which can provide the desired perception.

4.4 Research Through Media Art Installations

As noted by Rasmussen et al. [33] the current research on shape-changing materials lacks a focus on specific applications scenarios. Similarly, Alexander et al. [27]pointed out that there are no shared or proven evaluation methods for such interfaces. One of the reason is that most of the past and current research focuses on the development of enabling technologies. Even if an essential part of this thesis is devoted to the discussion and evaluation of new enabling technologies and mechanisms, we propose a method to evaluate shape-changing materials "in the wild". This method consists in developing first a scenario, which establishes a specific context and application area that guide the design and development of the system. Second, this scenario is tested by re-enacting the scenario in the form of a media art installation. Through this method, we can test our system before deploying it in the envisioned scenario. The research on shape-changing materials, both in HCI and Media Art is based on speculative methods and visions [101]. Even if prototypes can be built and tested, they are usually viewed as a proof-of-concept for future materials that are don't here yet. In order to make this speculation productive and meaningful for research we should refer to practices such as "Design Fiction" [102]. Design Fiction is a design practice used to explore possible future technologies through the development of a speculative scenario. Through this approach, design artifacts are used to illustrate such scenario with the purpose of generating debate and dialog around the social implications and impact of new solutions based on design and technologies. Iwata [103] noticed that media art exhibitions can represent an interesting platform for testing interactive systems outside the laboratory. From this point of view, hands-on demonstrations in an open environment should not just be considered a way of testing an interactive device, but also an essential step of the research process. This is more relevant for systems and interfaces characterized by unconventional interactions and unique appearances. Venues like Media Art festivals and exhibitions can provide many benefits for qualitative research. First, they help reach a huge group of possible users, composed of people of different ages, genders, nationalities, and degrees of expertise with interactive technologies. Second, such events remain open for an extended period, allowing people to try and evaluate the system freely. Third, by interacting with the audience, it is possible to conduct unstructured interviews. For our study, due to the difficulties of testing the system in a real scenario (hospital), we have designed an art installation to present Vital+Morph to the public. It represents an approximation of the experience we wanted to assess. This approach is used in many exhibits and museums for providing a context in which visitors can better understand artifacts. The installation was created as a way to test and narrate the scenario we developed.

We exhibited Vital+Morph during the Ars Electronica Festival and the Tsukuba Media Art Festival 2016. We had the opportunity of observing how a varied audience interacts with Vital+Morph, and of investigating their reactions and opinions.

5. CASE STUDY I: VITAL+MORPH

In this study, we introduce the development and evaluation of Vital+Morph, a prototype for a shape-changing interface for remote monitoring and physicalization of biometric data (Figure 5.1). Vital+Morph is composed of a series of reactive materials that can physically represent the vital signs of a patient located remotely in real-time, for the benefit of his/her parents and friends. Through this project, we aim to explore how the engagement and awareness of physiological measurements of a remote patient can be implemented through shape-change. We based the design on a fictional scenario involving a patient hospitalized in the Intensive Care Unit (ICU). The patients vital signs are physicalized at a remote location using the Vital+Morph system. In order to assess and prove the proposed concept, we developed an exploratory study in two steps. The first step involves the evaluation of the systems basic performance. The second step is a user study conducted during two Media Art Festivals, where Vital+Morph was presented as an interactive installation.

5.1 Design Rationale

In this section, we present the design rationale we followed for the development of Vital+Morph. First, we present the fictional scenario on which our design is based. Second, we illustrate the bio-inspired approach used to guide the process of form-finding of Vital+Morph. Third, we discuss how the desired functionalities have been developed through a series of non-interactive prototypes.

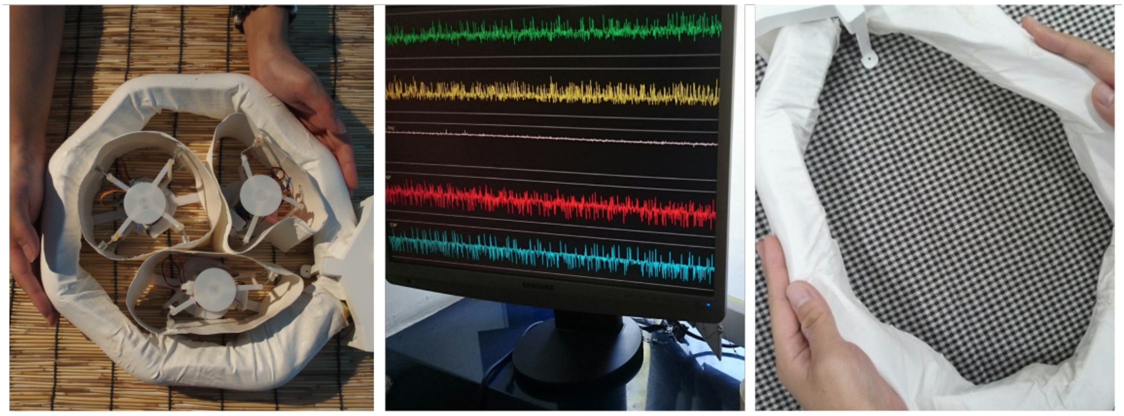

Fig. 5.1. A complete view of Vital+Morph and its main components. On the left, a complete Vital+Morph interface, composed of the Vitals (inside) and Morph (outside). In the center, software that simulates the functions of a vital signs monitoring station. On the right, another morph that can be placed at a different place from a and can communicate with it.

5.1.1 Fictional Scenario

We first developed a fictional scenario in the form of a written narration, as shown in Figure 5.2.

5.1.2 Bio-inspired Approach and Form Finding

For designing the form and the functions of Vital+Morph we used a bio-inspired metaphor based on diatoms. Diatoms are microscopic single-celled algae that are regarded as the most vital organisms present in oceans and freshwater ecosystems in general 5.3. We will outline the most important characteristics of diatoms, and how we used them to guide the design of the function, behavior, and appearance of Vital+Morph.

1. *Transformation of external stimuli*: Diatoms belongs to the family of phytoplankton. These are organisms that use photosynthesis to convert the suns

SCENARIO

"Mrs. Ohnuki lives in Japan with her husband Mr. Antonini and their two children. Mr. Antonini's mother, named Giovanna, is hospitalized in Italy following a difficult surgery. Since the couple lives in Japan, it is difficult for them to remain updated about the condition of Giovanna, which is quite complex. She suffers from respiratory issues caused by the surgery and also due to her age, which is 80 years.
The family in Japan has a Vital+Morph installed in their living room, barring the heart rate monitor, which Takeo, Mrs. Ohnuki's son, keeps near his bed. In the morning, the family members meet around the display and monitor the Vitals. They notice that the indicator associated with the respiration is moving slow, while the one that indicates the pulmonary arterial pressure is behaving erratically.
Before leaving home, Mr. Antonini takes these two Vitals with him. The other family members decide to split the others. In the evening, when they all come back home, they will put them back together. Before leaving, Mrs. Ohnuki slowly moves the Morph."

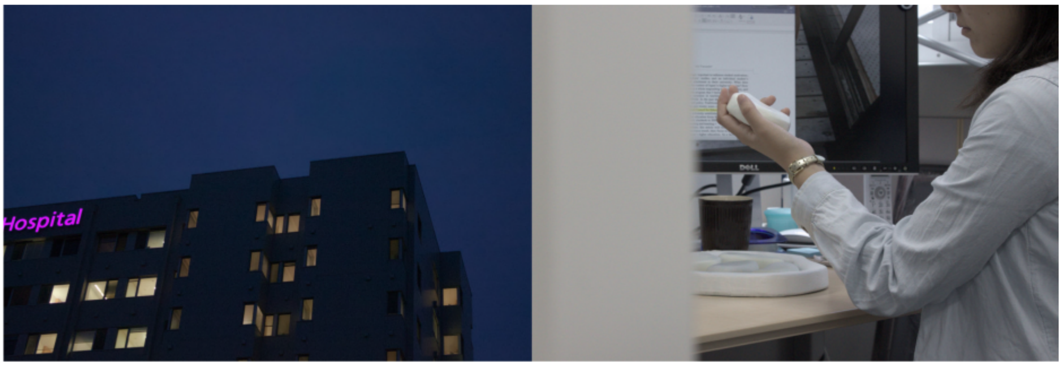

Fig. 5.2. A representation of the envisioned scenario: remote monitoring of a hospitalized person by a family member through the use of Vital+Morph.

energy into nutrients. Through a process of photosynthesis, take the suns energy and convert it into nutrients.

Vital signs represent the nutrient of the material that is brought to life by translating abstract data into physical motion and shape change.

2. *Deformability*: Diatoms not only take nutrients from light, but they also absorb them through the water. This is made possible by the elaborate perforations

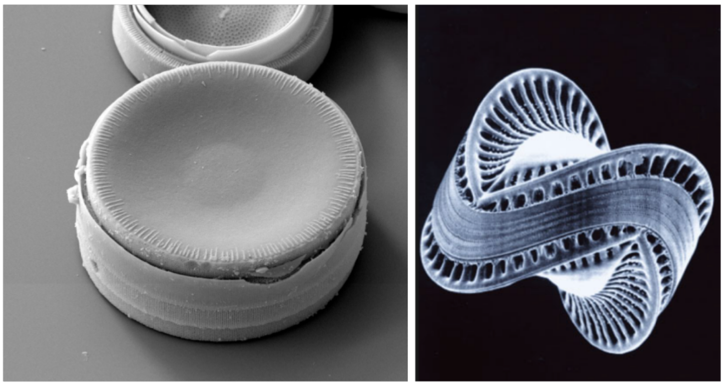

Fig. 5.3. Two magnified views of diatoms.

on their shell, made of a silica-based material. The cell wall is composed of a cytoskeletal structure called frustule that consists of two halves. The combination of the structural and the material qualities allows diatoms to perform significant deformations of their overall structure in order to withstand high loads.

Deformability became an essential aspect of the design of our interface. We decided to distribute different degrees of deformability among the different elements. The received data deform one element to display them through its surface, while the users can actively deform another.

3. *Morphology*: Diatoms grow as single cells. However, they can form filaments and simple colonies. Such colonies are composed of cells connected usually by organic threads or by attaching to different substrates like plants.

   From these characteristics, we derived the modularity and spatial configuration of the global Vital+Morph interface as a colony of physicalizations.

4. *Monitoring and information retrieval*: Diatoms are often specific to particular habitats because they exhibit tolerance to different environmental variables such as the chemical composition of the water in which they live. As a result, diatoms are used extensively in environmental assessment and monitoring. Since the

silica walls do not decompose, diatom shells found in marine and lake sediments are used to interpret historical conditions of the environment.

Even though in Vital+Morph we have not incorporated the possibility of retrieving historical information, this function of diatoms, which allows them to display information through the characteristics of their shapes, is a fundamental concept used for the design of the interface.

5.1.3 Design Requirements and Systems Functionalities

We explored the possibility of using diatoms first for form-finding, and then to specify the different behaviors concerning the target application scenario (Figure 5.4). First, we developed a series of mock-ups using paper to sketch and test the design metaphor. Second, we used such mock-ups to design the interactions, outline the main components, and their functions. Then, we started to specify the design guidelines.

Fig. 5.4. Three studies of the form and spatial layouts of Vital+Morph inspired by diatoms. On the top a paper model, a graphical representation, and a physical model used for testing the possible shapes and dimensions. On the bottom, a study of the interactions.

1. *Dynamic physicalization of vital signs*: The Vitals must be the core elements of the system, and should be designed for making data perceivable to human senses. Each Vital must:

   - be able to receive a specific stream of data and display it through deformation of its surface;
   - address both the visual and the tactile channel through shape-change;
   - act as a physical surrogate of a remotely located patient;
   - be self-contained and autonomous (both in terms of power and communication capabilities) and have a dimension suitable for humans hand.
   - be designed as a material that responds to digital events.

2. *Support remote touch*: If the Vitals must be designed to display vital signs coming from a hospital, the Morph must be designed to accomplish the opposite function. Mostly, the Morph must enable two-way communication between two remote places (the house and the hospital). The Morph must perform three main functions:

   - should act as a constraint for the Vitals by delimiting the area where they can be placed;
   - should be suitable for remote communication through shape-sharing;
   - should support both direct input and provide haptic feedback on the same surface.

   By linking two Vital+Morphs through an internet connection, it should be possible for the patient and his/her relatives to communicate through the Morphs. The deformations caused on one side are reflected on the other interface. Like the Vitals, the shape-changing characteristics of the Morph should be able to address and appeal both the visual the haptic senses.

3. *Spatial Relations, Social connectedness, and co-monitoring*: The combination of Vitals and Morph creates the complete system. The relations between these two elements must be spatial and must lead to two different user experiences:

    - *Multiple monitoring*: When both Vitals and Morph are combined, the five Vitals can be observed together. Users in the home must then get an overview of the overall status of the vital signs measured on the patient in the hospital. Substantial changes in data can be detected by just observing the surfaces deformation and such as frequency and speed of the shape-change;
    - the Morphs should be designed to encourage multiple group activity;
    - users should also be able to remove the Vitals from the Morph and carrying them in different places and move from a co-monitoring activity to a more private and intimate.

In the current application, we designed five Vital elements. This corresponds to the number of fundamental vital signs. All five Vitals are placed inside a Morph, which is connected to another one, placed in a different location.

5.2 Implementation

In this section, we introduce the implementation of Vital+Morph. The main components are: a software that simulates a vital signs monitoring station, and the physical artifacts, referred to as Vitals and the Morphs. The basic system architecture is shown in Figure 5.5.

5.2.1 Simulation of a Vital Signs Monitoring Station

The first step in the development of a simulation of a Vital Sign Monitoring Station was the choice of the signals. We carefully select actual recordings of a

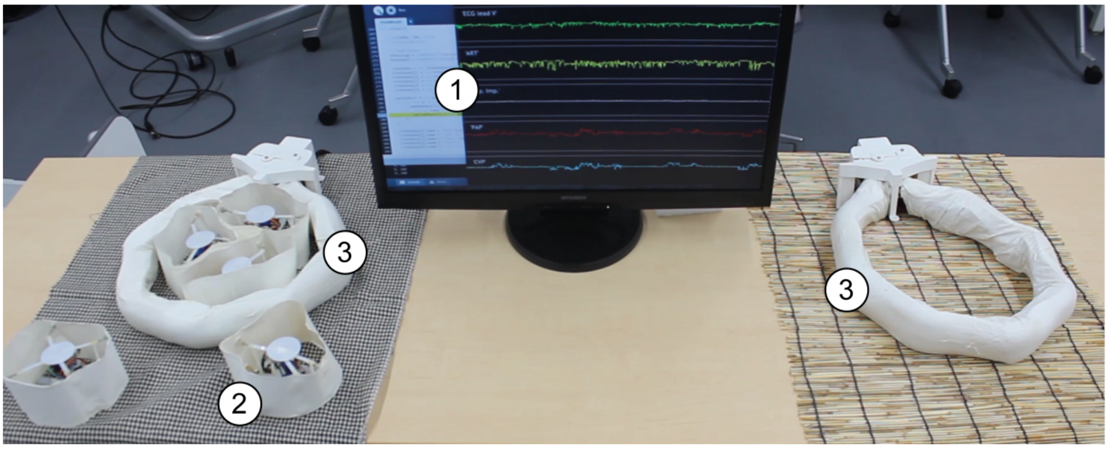

Fig. 5.5. A view of the complete prototype. (1) simulation of a Vita Signs Monitoring Station; (2) Vitals; (3) Morphs.

patients vital signs from the PhysioBank[1], a public database of physiological data. To match the proposed scenario, we selected a 24-hours recording of an eighty-year old woman hospitalized after surgery, who suffers from respiratory problems. From such dataset, we extracted the five main vital signs: heart rate (pulse), arterial blood pressure (ART), pulmonary arterial pressure (PAP), central venous pressure (CVP), and respiratory rate.

We developed a software for simulating the tasks of a vital signs monitoring system and for managing the wireless communication (Figure 5.6). At first, a text file containing the dataset is read. Then, each data is scaled and formatted for transmission to the corresponding Vital element. We choose Bluetooth as a communication protocol. The scaled data are directly mapped to the control of each Vitals actuators (Figure 5.7). We implemented a function to control the frequency of the input data and change the level of the mapping between the signal and the degrees of rotation for controlling the rotation of the actuator in the Vitals. To complete the simulation, a standard wave plot-style visualization is also provided.

[1]https://www.physionet.org/physiobank/

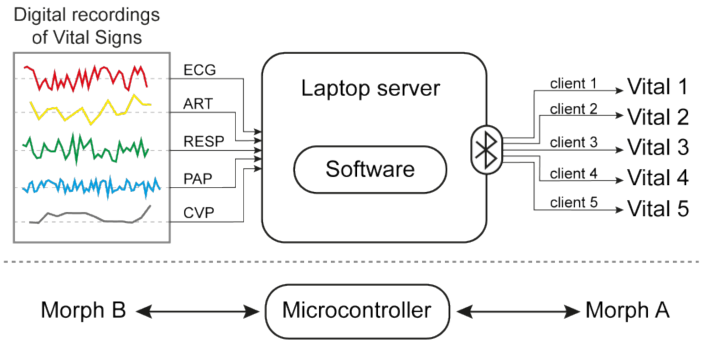

Fig. 5.6. Representation of the communication flow in the Vital+Morph system.

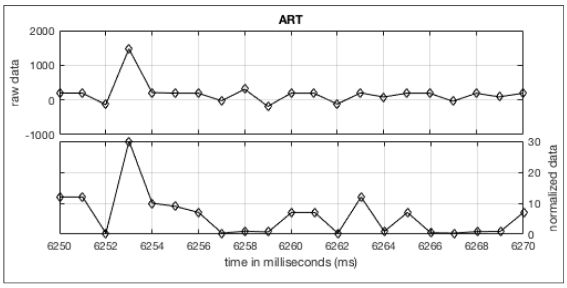

Fig. 5.7. A sample of the arterial pressure (ART) measurements that show the relations between the raw signal (original 1000 recordings of vital signs) and the normalized version processed by the software.

5.2.2 Vitals

The Vitals are composed of a deformable cylindrical surface, an embedded actuation system, a microcontroller, a Bluetooth transceiver, and a power source. The basic system is outlined in Figure 5.8. We designed an actuated surface that resembles the appearance of a diatom, as outlined in the previous section. The surface of the Vitals was fabricated using a cylinder made of paper coated with liquid latex. This offers the advantage to prevent tearing of the paper, and increase both the deformation effect and softness of the surface. The cylindrical surface is then attached to the bottom of the actuation module through a plastic stand. This prevents the cylinder from moving freely, and at the same time, it stabilizes the deformation.

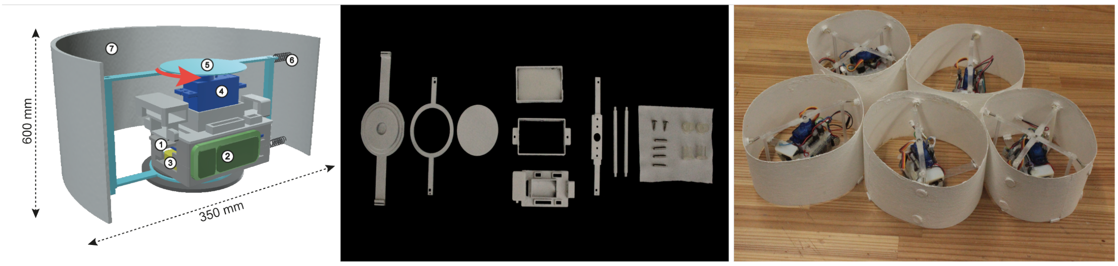

Fig. 5.8. Vitals. Left: a section of the Vital highlighting the different components: (1) microcontroller, (2) bluetooth transceiver, (3) lithiumpolymer battery, (4) servo motor, (5) shaft and direction of rotation, (6) spring, (7) paper cylinder. In the center, the mechanical components of Vital+Morph. On the right: the five Vitals used in Vital ? Morph. b The deformations produced by the data stream on one Vital (ECG).

The core element of the Vitals is the actuation system, which is responsible for translating the data into shape-change and then haptic feedback. For fulfilling the requirements about portability and self-power, we used a micro servo-type actuator (9g Micro Servo Motor, 4.8V). Servo motors enable precise control of angular position, velocity, and acceleration. We designed the actuation system to create a change in geometry: when the motor moves, it causes a deformation of the shell. Each servo motor is equipped with four extended horns, two on the upper part connected directly to the operating shaft of the motor, and two on the lower part. These two sets of horns are then joined together through two vertical connectors. The end of each horn is attached to the surface through a small spring. The physicalization of the data is then produced as follows:

1. The corresponding data are received through a Bluetooth module and scaled in the microcontroller (Arduino Pro Mini 3258) to match the PWM frequency that controls the angular position of the motor (degrees).

2. When the shaft of the servo rotates, the springs pull the surface. Such displacement causes the cylindrical surface to deform.

3. The mapping between the data and the motion was designed as when the data received are at their minimum value, the shaft of the actuator is positioned at 0 degrees. This represents the initial state when each Vital appears to be a perfect cylinder.

4. The springs not only contribute to deforming the surface but also produce a noticeable force every time the servo motor rotates. In other words, each time the values of the data change from low to high (and vice versa) the actuator moves and the springs release a force.

5.2.3 Morph

The Morph is a robotic I/O surface, composed of a closed-link system of actuators and joints (Figure 5.9). Differently, from the Vitals, where the deformation occurs in response to data, the deformation of the Morph is produced directly by users. When users deform with their hand one Morph, the deformation is transmitted to the corresponding Morph, which will act as a display. We defined this function as shape-sharing. The Morphs also have a circular shape, like the Vitals. The system is composed of eight actuators linked together. As actuators, we choose an analog-feedback servo motor (Adafruit ID:1404), which can provide both position sensing and mechanical movement in a single element.

In the current prototype, two Morphs are connected and synchronized through an Arduino Mega micro-controller. We employed a direct mapping between the position sensor of the actuators in one Morph and the position control of the motors in the linked Morph, and vice versa. To enrich the tactile qualities of the device, the actuators are covered with a soft surface composed of an elastic fabric reinforced internally with sponge material.

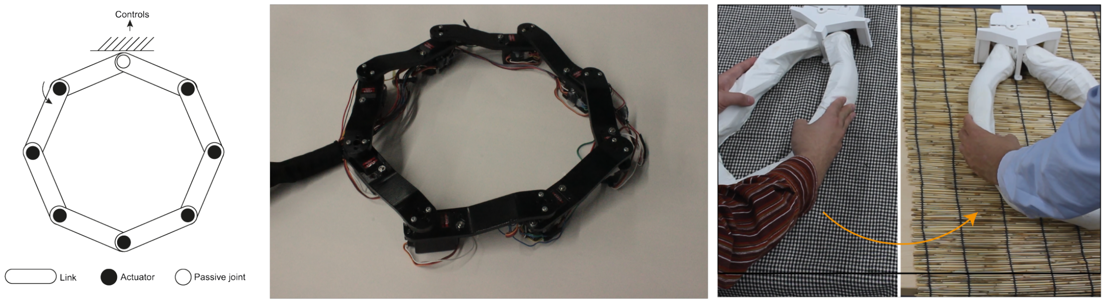

Fig. 5.9. Morph: on the left, the closed link system of the Morph elements; in the center, an image of the assembled mechanism without the soft cover; on the right, two interconnected Morphs with the soft cover.

5.3 Performance evaluation

We wanted to assess two main design requirements: the ability of the Vitals to produce perceivable haptic feedback, and confirm that two interconnected Morphs can correctly transmit their shape.

5.3.1 Haptic characteristics of data physicalization

We measured the force produced by one Vital when reproducing the data set through shape-change. A piezoelectric force sensor (FlexiForce B201) was attached to the index finger of a subject (Figure 5.10). We recorded the angular position of the motor of the Vitals, and the voltage produced by the sensor when the surface of the Vital was touching the subjects finger. We repeated the measurement five times one for each type of data. The duration of each recording was ten minutes.

In Figure 5.11 the results are presented. We can observe that a force is generated when there is a consistent change in the data (peaks). At its highest value, the recorded force corresponds to a maximum of 0.8 N, which can be perceived by an average human. We can also notice that the quality of the haptic feedback changes

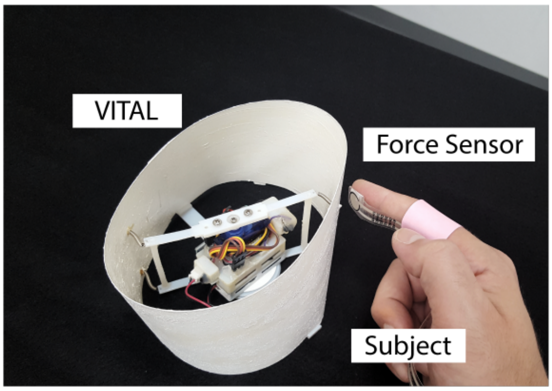

Fig. 5.10. The apparatus used to measure the reaction force produced by the Vitals on a user's fingertip.

for each vital sign. In the case of respiration data the force produced is not continuous. The reason is that the patient has some respiratory difficulties. Through such evaluation, we confirmed that the Vitals could provide haptic feedback based on some characteristics of the data, such as their changes between maximum and minimum. This shows that changes in geometry cannot only be perceived through vision but also with the sense of touch.

5.3.2 Shape transmission

We performed a series of measurements to assess the amount of error that occurs in the transmission of shape between two linked Morphs. We compared the shape produced on one Morph by users deformations, and the shape transmitted to the other Morph. As deformations, we selected three gestures: (1) horizontal squeeze, (2) vertical squeeze, (3) a gesture randomly selected that cannot be classified in the previous two categories (Figure 5.12).

Such gestures are based on preliminary observations of users activity. The first two gestures represent the maximum contraction possible, in the horizontal and vertical axis. The third category includes more subtle deformations that can be performed globally but also in just a section of the Morph. To measure the correctness of the

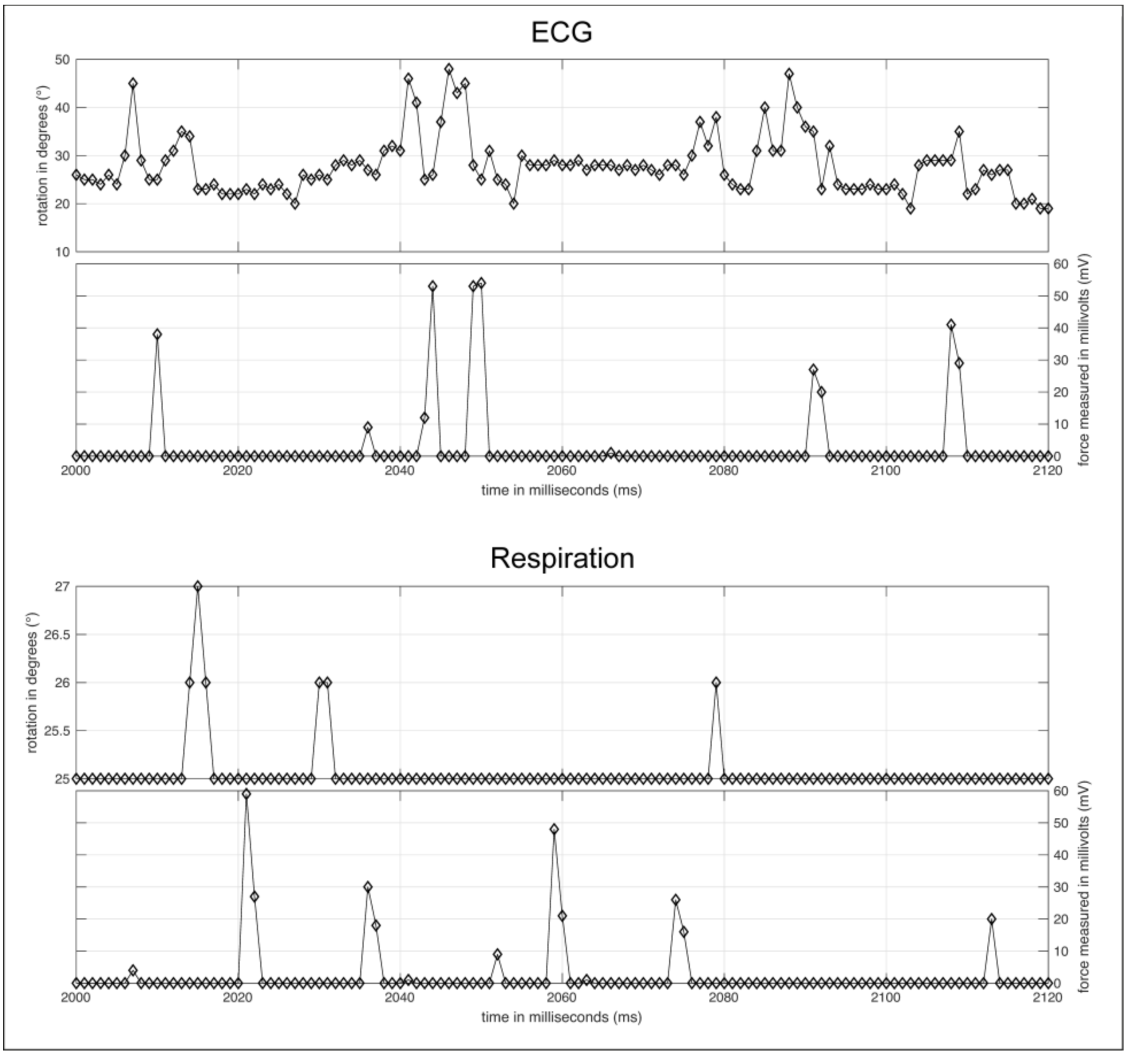

Fig. 5.11. Two samples that show the relation between the position of the actuator (corresponding to the measured vital sign) and the force measured on a users finger. The chosen samples are for the electrocardiogram and the respiration impedance.

shape-sharing mechanism we compared the areas of the two Morphs (Figure 5.13). The test was performed by placing two Morphs close to the each other. We recorded ten trails for each gesture with a video camera placed on the top. We then selected from the video recordings the moment where the shape transmission happened. The

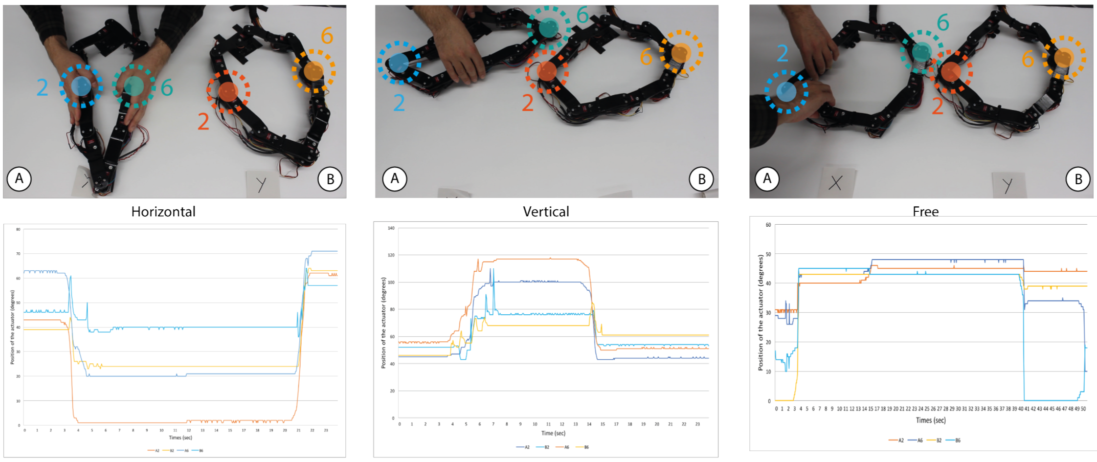

Fig. 5.12. Examples of the reproduction of the shape between transmitting (A) and receiving(B)Morph. Three different gestures are presented: (1) horizontal-type squeeze, (2) vertical-type squeeze, (3) free-type of deformation. On the bottom, a plot of the rotational position of the actuators.

corresponding footage was selected, and we traced the outline of the shape of the Morphs. By superimposing a grid made of equal cells, we calculated the area of each shape using the Pick's theorem.

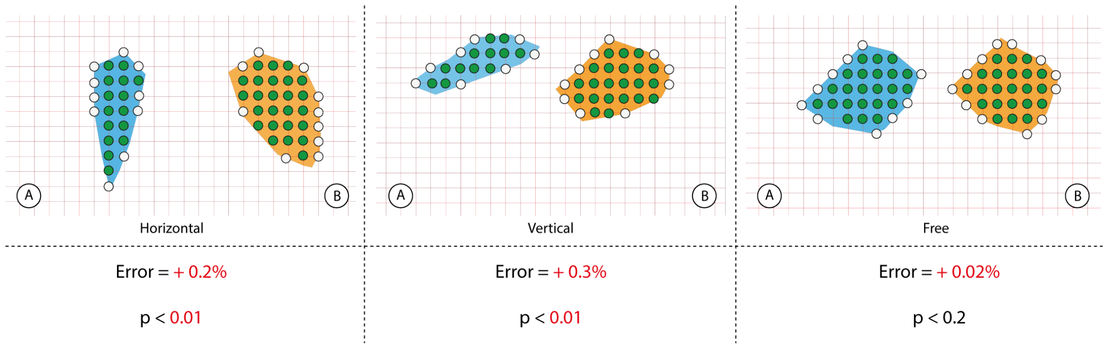

Fig. 5.13. The application of the Pick's Theorem on the shape of the Morphs.

For each condition, we calculated the mean area for the sender (A) and the receiver (B) Morphs, and by subtracting the means we the difference between the two areas. Subsequently, we calculated the percentage of the error between the (A) and (B) Morphs. It was found that the lowest error is observed in gesture 3 (+0.02%). For the horizontal and vertical, the error is respectively +0.3% and +0.2%. We then confronted these results by running a t-test, to check if the two shapes (A and B) are the same. The third gesture reported a $p < 0.2$, while the first and second gestures reported a $p < .01$. We can confirm that the better results are obtained with the free-type gesture. This can be explained by the characteristics of the three types of deformations selected. The horizontal and vertical represent two extreme contractions. However, the third type of deformation is the most closed to an interaction that a user can have with the Morphs. We can conclude that it is challenging to reproduce extreme contractions or expansions. One of the reasons can be found in the friction produced between the actuators at the surface. Another relevant element that influences shape-sharing is time. Time dictates how fast the deformation is and for how long the act of deformation is performed. We observed that slow deformations (> 45 seconds) generate better results, while faster deformations are more likely to affect the accuracy of transmission negatively.

5.4 User Study

We exhibited Vital+Morph at the Ars Electronica Festival (Linz, Austria) in September 2016, and the Tsukuba Media Art Festival (Tsukuba, Japan) in December 2016. Ars Electronica is one of the major international events in the field of Media Art, while the Tsukuba Media Art Festival is a local event. During these occasions, we had the opportunity to observe and investigate how the audience approaches, perceives, and interacts with Vital+Morph.

5.4.1 Methodology

We conducted a users study using a mixed method of observations, notations, and non-structured interviews. The aim of this study was to understand the broad understanding of Vital+Morph and examine how users perceive shape-change. Moreover, we were also interested in obtaining a better understanding of the social impact of dynamic data physicalization concerning a particular application scenario.

5.4.2 Subjects

During the exhibition at the Ars Electronica Festival, more than 600 people visited the installation. The festival lasted for five days, and the exhibition was opened eight hours per day. We observed around 200 people actively interacting with Vital+Morph. Out of this number we interviewed 40 visitors. At the Ars Electronica Festival, the audience was composed of both males and females, with an average age between fifteen to seventy years. Most of the visitors were from European countries, USA, and Asian countries like Japan, China, and Australia. At the Tsukuba Media Art Festival, the vast majority of the audience was Japanese. Moreover, here, the gender distribution was almost equal, with a similar age distribution. Differently, from the Ars Electronica Festival, which the audience is composed of media art enthusiasts, in Tsukuba, a significant number of visitors was composed of families with young children. The Tsukuba Media Art Festival lasted for eight days and was open seven hours per day. Being a local venue, the number of visitors was lower compared to the Ars Electronica Festival. This resulted in around 200 people visiting our installation and 100 interacting with our system. Here we interviewed 20 participants. At both exhibitions, the audience were first time users of Vital Morph.

5.4.3 Exhibition Design

The installation version of Vital+Morph was designed with the aim of replicating the scenario (section) to help visitors to contextualize the system (Figure 5.14).

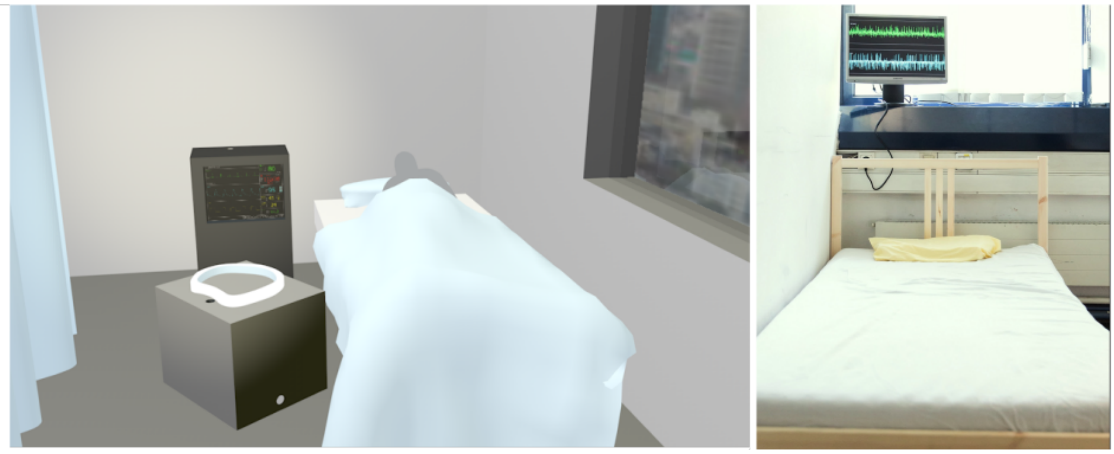

Fig. 5.14. The installation version of Vital+Morph used to illustrated the scenario.

All elements present in the installation have been chosen to support the narrative outlined in the scenario. The exhibition space consisted of a unique room divided into two spaces: a “home” area and a “hospital” area, divided with a curtain. When the audience first enters the room, they face the home area. Such area plays the role of the room of a house where people can gather around Vital+Morph, which was placed on the top of a white plinth, and illuminated by a spotlight. When the audiences cross the curtain, they entered the “hospital” area (Figure 5.15). Here we created a simplified version of an ICU, composed of a bed and a monitor, to provide a plot visualization of the vital signs. On a second plinth, we placed a Morph element. Both bed and Morph were illuminated through two spotlights.

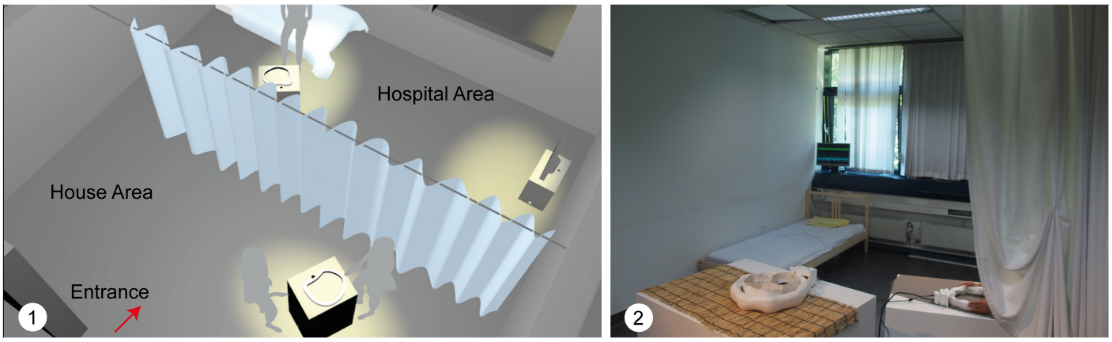

Fig. 5.15. The installation version of Vital+Morph. Left: a rendering of the space; right: the actual set up at the Arts Electronica Festival.

5.4.4 Procedure

Each visitor was first introduced with a verbal explanation of the concept behind Vital+Morph and a narration of the fictional scenario. We did not inform on how to interact with the interface in advance, and they were able to experience Vital+Morph without any time constraints freely. In both exhibitions, visitors were composed of groups between two and six people. Single visitors were rare. We observed users behaviors and noted down the sequence of their interactions. Then, we asked users few specific questions related to the perceptual qualities of the interface. Lastly, we encouraged visitors to express their opinions regarding Vital+Morph. We collected their answers, and subsequently, we selected the most common and significant responses.

5.5 Results

In this section, we present the results of the study. We first present the observations regarding the behavior of the users, and then we report the answers provided by visitors regarding their experience.

5.5.1 Observations

By analyzing our notes, we recognized a series of recurrent interactions. We categorized them by following the order in which they happened and then divided into four groups (Figure 5.16).

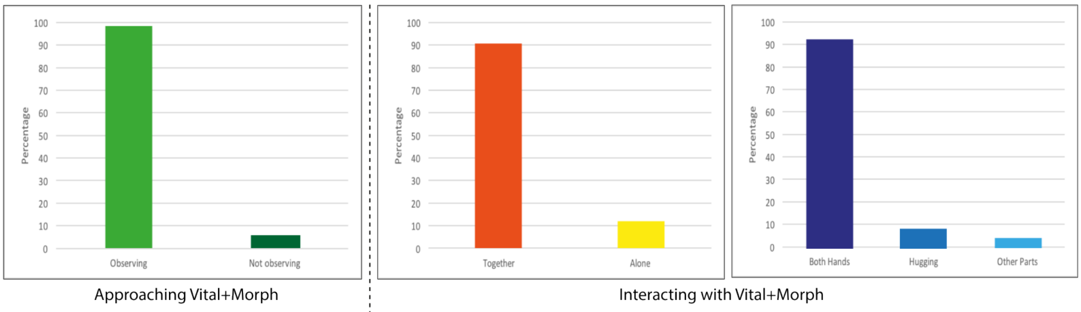

Fig. 5.16. Results of the observations of users' behavior.

1. *Observing and exploring*: We noticed that most users approached Vital+Morph by observing it. If the visitors were a group, they gathered around the plinth where Vital+Morph was placed. After a period of observation (which typically lasted between one to three minutes), users started to touch different parts of the interface. Since Vitals were constantly, they attracted the attention of visitors immediately.

2. *Re-composing and de-composing*: After a brief inspection, usually one of the visitors started to explore the interface by grabbing one Vital and removing it from the Morph. We defined this action as *de-composing*. By holding it in his/her hands, the user started to report verbally to the other visitors his/her feelings and thoughts. Then, such user with the Vital was passing it to other users. For instances, parents were giving it to their children. After this, other users started to grab the remaining Vitals. With the Vitals in their hands,

people were actively speaking with the other members of the group about their tactile experiences. At this point we also observed visitors exchanging different Vitals among them with phrases like "*pass me the heart beat*" or "*take the respiration*". Visitors were also walking around the room while holding the Vitals. The second action we observed was when the users put the Vitals back inside the Morph. We named this action as *re-composing*, which can be considered as a consequence of the *de-composing* action. We observed that most people *re-composed* the interface together, and only a few them alone. Subsequently, when Vital+Morph came back to the initial state, the visitors reverted to the observation phase.

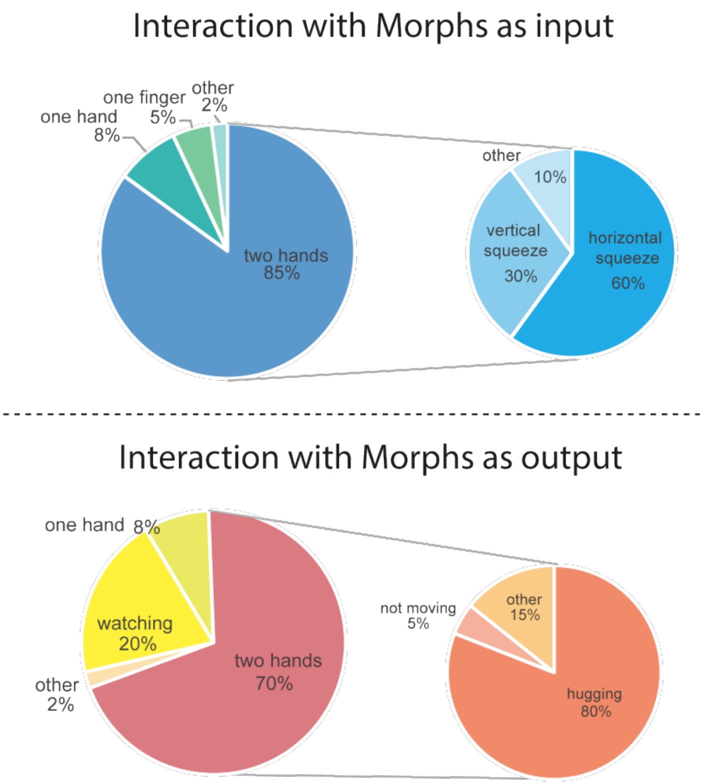

Fig. 5.17. Interactions with the Morphs as an input device and as an output.

3. *Shape-sharing*: Between the actions of de-composing and re-composing, when all the Vitals were removed from the Morph, visitors started to pay attention to the Morph (Figure 5.17). Compared to the Vitals, the identification of the functions of the Morph was slower and usually developed through several steps. Usually, this happened when visitors crossed the curtain and moved in the "hospital" area. Here they discovered the other Morph near the bed. We noticed that usually users would sit on the bed and start touching the Morph placed in front. Then, visitors identified that the two Morphs were synchronized when a person in the "house" was notifying the other with sentences like "*Its moving!*" or similar comments that showed that the interface was responding. From this moment, users on two sides started to explore possible ways of interaction with the Morphs. Most users were manipulating the Morph with two hands, some with one hand, and very few with a single finger or other body parts, like their arms. Some of the most common actions performed with two hands were squeezing the interface horizontally and vertically. A tiny percentage of users tried to perform other types of manipulations. This can be noticed by looking at the recordings of the position sensors of the actuators in the Morphs (Figure 5.18). We then observed that most users tried to deform the Morph very quickly at first. However, after some attempts, they tried to reduce the speed of their movements and to perform their actions slower. The interaction with the Morphs was usually longer compared to the one with Vitals. We noticed that the users that spent more time interacting with the Morphs (> 5 minutes) were keen to try different manipulations.

4. *Tactile communication*: However, the use of the Morph was not limited to deform its surface. Before responding to the stimulus, users were taking time to feel the deformations produced by the Morph on their own body. Similarly to manipulation, deformations were also felt mostly using both hands. We also observed many users placing their arms as mimicking hugging. Very few tried to use other body parts, such as the face.

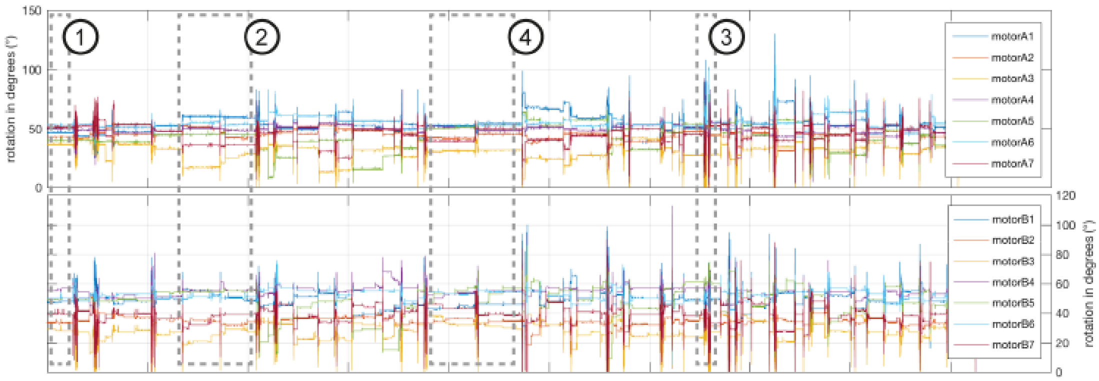

Fig. 5.18. Recordings of the interactions between two Morphs. We can devise four types of gestures performed by users: (1) still, not moving, (2) vertical squeeze, (3) horizontal squeeze, (4) other type of deformation.

5.5.2 Interviews

After analyzing the answers and comments provided by users, we identified six major topics related to emotional response, design choices, tactile and kinesthetic communication, social impact, and criticalities. The main answers are summarized in Figure 5.19.

1. *Emotional response*: The first types of questions posed to users were about their emotional response to their overall experience with Vital+Morph. The most recurrent comment referred to the visual perception of the Vitals. Comments can be summarized with the expression it looks like a living organism. Visitors expressed similar ideas by referring also to "organs", "insects", or "hamsters". Then, when referring to the tactile experience of grabbing a Vital, users described this experiences like "*its like holding a human heart*", or "*I feel like I am touching a blob*". Some also commented on the force produced by the Vitals. One user described "*The force I feel, its kind of pulsating (...) It moves in my hands. I can feel something rhythmical. Its constant but sometimes it changes.*

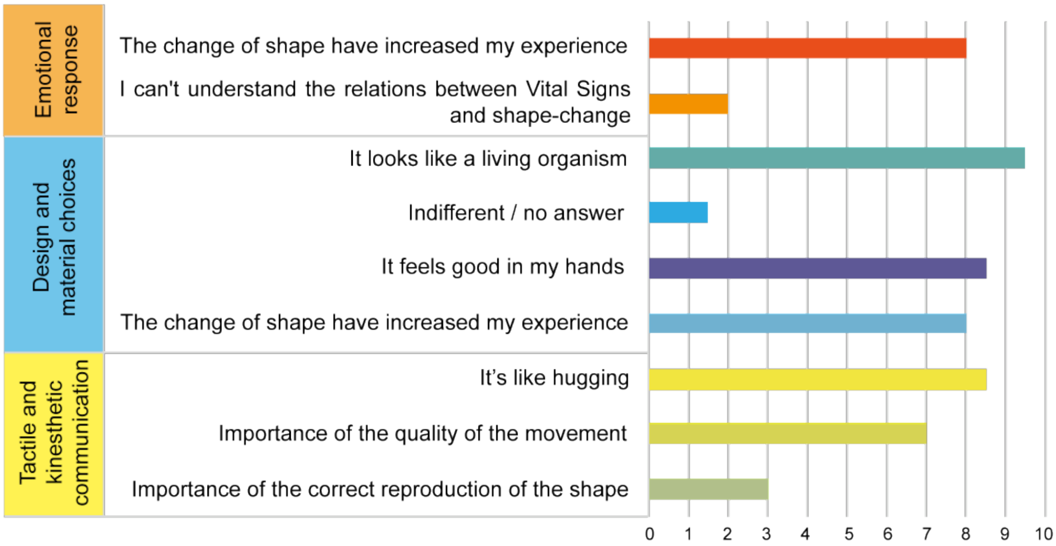

Fig. 5.19. Results of the interview process.

I think its something alive". Such comments were given independently from the vital sign displayed by the Vitals. We can see how users strongly identified the system with something living, and related their experience with imaginative ideas, like holding a pulsating organ in between their hands. Aside from such comments, some users felt a sort of mismatch between the feelings and the ability to understand the meaning of the shape-change. "*I can feel, yes, but I dont know exactly what it means*". Others commented that they feel the need of more clarity in the representation of data "*I dont know if this movement is right or wrong*", or "*I would like to have a reference point. For example, I dont know how to judge this motion. Is this heartbeat rate good or not?*". However, when asked to comment if the change in shape increased their perception of data, most of the visitors answered positively.

2. *Design and material choices*: We recorded a general appreciation of the tactile qualities of Vital+Moprh, through comments like "*It feels good in my hands*",

Fig. 5.20. Visitors interacting with the Morphs: a at the Tsukuba Media Art Festival (left) and at the Ars Electronica Festival (right).

or "*I like the feeling when Im touching it*". Such feedbacks referred both to the use of active touch when deforming the Morphs, and passive touch, when holding the Vitals. Children were especially attracted by the possibility of being engaged in different haptic experiences. Through these comments, we can see that the choice of materials plays a critical element in the design of shape-changing interfaces.

3. *Tactile and kinesthetic communication*: Another element we investigated was the interaction with the Morphs. Contrary to our expectations, users valued the quality of the movement produced by Morphs more important than the correct reproduction of the shape. Moreover, many users commented on the difference between fast and slow movements: "*When Im using it (the Morph) I like to move it fast. When I receive it I like slow movements*". However, some users found difficult to understand how the shape-sharing communication has to be performed. "*This seems to be a conversation. Two people communicating (...) but I have never experienced something like this (...) however its fun*";

Fig. 5.21. Visitors interacting with the Morphs: a at the Ars Electronica Festival (left) and at the Tsukuba Media Art Festival (right).

"*I have no idea no idea how to develop a way of communicating. I mean, it seems easy, you have just to move it. But I dont know what it means. Especially I dont know the meaning when I see the answer when the other persons motion is played on the one Im facing. I dont know*". Some users highlighted that the absence of audio and video for remote communication resulted in a diminished experience: "*Usually I use the phone or Skype to communicate with friends. This is something that I have never experienced. You have to touch it*". When asked to comment on how they perceived the Morphs, users related the experience to the one of hugging and embracing another person. "*For me this is similar to hugging, like when you hold a person with your arms*"; "*I will say that it reminds of the gestures you use when you embrace someone, usually a parent, a friend*". In relation to such experience, some users felt that in order to be a real physical experience temperature (like cold or warm) is required. "*In order to communicate the sensation of hugging, and especially the feeling that another person is being hugged, besides the force and the shape, the warmth* *of the arms are significant. Without it it is just like cold, like technology*"; and "*I would like to feel the temperature of the others, like the warmth or coldness of the hands*". However, the majority of visitors said that these characteristics of the Morphs improved their feeling of being connected to another person. An interesting comment was "*Its very abstract butit makes me imagine the other person*".

4. *Social impact*: In the last part of the interview process, we asked the visitors to freely comment on the possible introduction of Vital+Morph in their lives. Most of the visitors expressed surprise and interest in the system. This is probably related to the fact that most users have never experienced a shape-changing interface before. Also, the application of Vital+Morph generated a positive interest, especially in visitors of age > 40 years. They often related their experience with Vital+Morph with their private stories of having parents or relatives hospitalized in reanimation or Intensive Care Units: "*I remember when my mother was hospitalized years agoI cannot say if I wanted to have this (Vital+Morph) at that timebut it makes me think (...) actually, I was really nervous sometimes because of the distance (...) however, I dont know because I have never used something like this (Vital+Morph). But the distance, the sensation of being powerless was high*" or "*Last year my brother was in a hospital after surgery, I was thinking what would have been (...) because its true in these situations you are not aware of what is happening, you are distant. You can visit them only a few times. Especially like me that I was living far away. He was not able to talk at the phone for weeks*". We should note that many of the oldest members of the audience suggested that an interface like Vital+Morph can be very useful in the current aging society because it can add a more physical and tactile dimension to distant communication: "*You know, here in Japan we are an aging society. People are getting old and the younger are very busy*"; another "*I think it can be really useful in the future. We lost contact with people, physical contact. I will encourage such ways to create a more physical contact*

among people". We were also able to collect opinions of a group of visitors that work in an Intensive Care Unit in a hospital in Austria. They emphasized that one of the main issues in ICU lies in the communication between the ICUs and the outside. In their opinion, finding a novel way to connect people is extremely important: "*In an Intensive Care Unit, everything is very complex, even the lightthe communication is really problematic*"; while another added: "*I have never thought about this possibility (...) its a strange concept*", "*its true communication there (in the ICUs) its a real problem, especially with the outside*".

Fig. 5.22. Visitors interacting with Vital+Morph at the Tsukuba Media Art Festival.

5. *Critical points*: We also recorded some very critical reactions. Some users expressed them at the end of the interview. One explained that "*its a very creepy (...) I dont want it*"; another "*Its noisy, its weird (...) I dont knowwhen I see all of these things moving (the Vitals) like this (makes a gesture that mimics their movement, like wobbling) it makes me suffering because seems to me that someone is suffering*". A third articulated her concern more strongly "*I will be really scared of having such a device in my house (...) and if it will stop? (...) this can become a strong reminder of death*". Such visitors expressed their concerns about sharing a physical space (in their daily life) with a real-time

physicalization of vital signs by describing it as “invasive”. Especially, they said that it will be challenging for them to handle a surrogate of a person who is probably suffering. Finally, according to several users, the systems malfunctions or errors can become a serious issue, since they can be related to tragic events, like death.

5.6 Conclusion

Our user study confirmed the effectiveness of our prototype, both concerning conceptual understanding, design metaphor, and haptic interaction. We gathered very insightful comments from visitors. Especially the negative ones underlined the fact that shape-change is a very powerful way of presenting abstract data. Despite being critical, users were not indifferent and were proactive in envisioning and proposing specific usage, and considering the possible social impact of an interface like Vital+Morph. This project contributes to the research on shape-changing interfaces in two ways. First, by providing a novel design metaphor inspired by a bio-inspired principle, which marks a departure from previous examples that have been based on common statistical ways of presenting data through histograms and pie charts. Second, through the evaluation methodology through a Media Art installation; this presents an alternative way to test novel systems and observe reactions of first-time users.

Through the development of Vital+Morph, we explored a design approach to represent data and make remote monitoring a social activity and a new form of data domestication. In this era, we are witnessing a convergence between digital fabrication, smart materials, and interconnected devices. It is then important to develop strategies and methodologies for making abstract data perceptible to users and integrate it into our daily lives.

6. CASE STUDY II: VOLFLEX++

Through this project, we explored the Volflex system as an enabling technology for creating shape-changing interfaces that can represent arbitrary three-dimensional objects with variable size and rigidity. By using a new implementation of Volflex, we conducted a psychophysical study to understand the haptic perception of the changes in size and rigidity. Such type of evaluation has never been done for shape-changing interfaces. First, we describe how the Volflex technology was implemented in our system, and provide a technical assessment of its basic characteristics. Second, we introduce the procedure of the psychophysical experiment and its results. Third, we discuss the results concerning previous works on the haptic perception of size and rigidity. Finally, we propose a proof-of-concept application that takes into account the findings of the user study, and proposes a method to implement the Volflex system in the context of Virtual Reality. While previous implementations of Volflex focused on general visual feedback, we propose a framework for mapping the characteristics of the balloons such as size and rigidity to 3D graphics and sound physical models. Both mapping and audio have been left out from the current research on shape-changing interfaces, however, they can increase the realism in the interaction, and open to new expressive possibilities using malleable media.

6.1 Method and Implementation

We manufactured two balloons and the relative control systems, based on the technique presented in [87]. We then used the system to conduct a psychophysical experiment to characterize the human perception of the change of rigidity and size using this interface. We measured sensory thresholds and used the results to derive the corresponding psychophysical metrics such as the Point of Subjective Equality, Just-Noticeable Difference, and Weber Fraction.

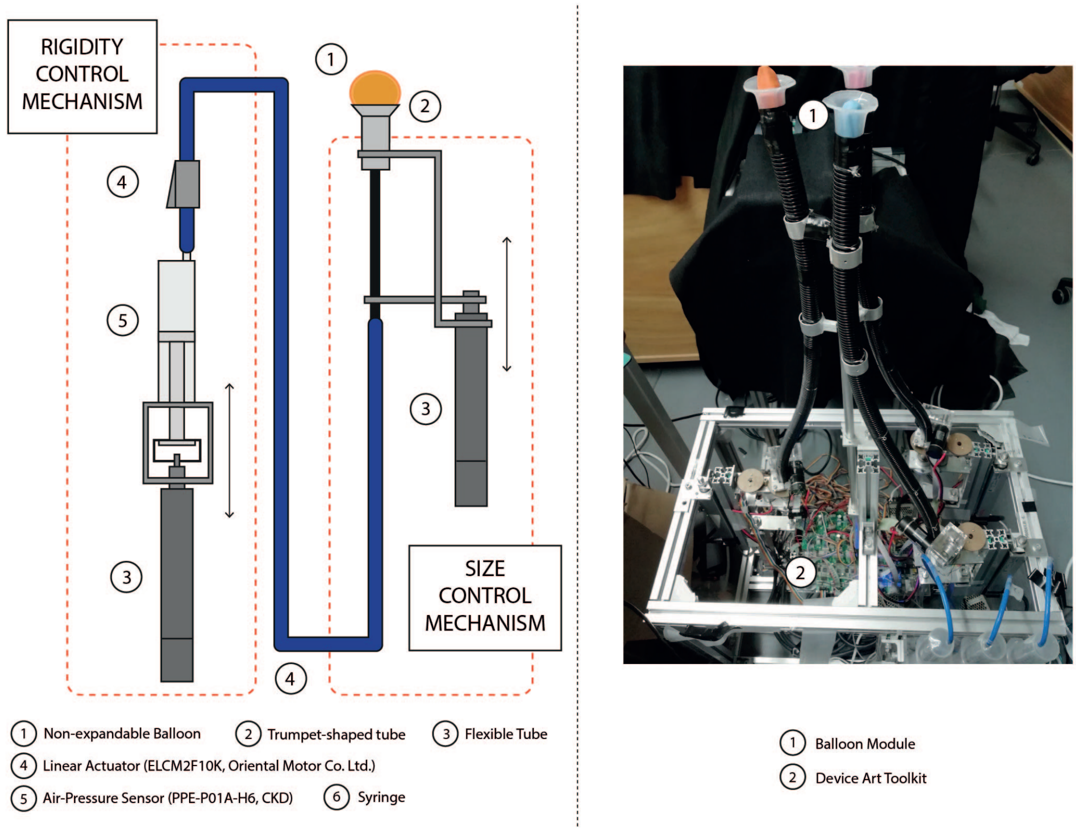

Fig. 6.1. Mechanical configuration of the system for one balloon. The system consists of one mechanism for size control, and one for rigidity. The two mechanisms are independent, but can be used simultaneously.

6.1.1 Device Design and Control Mechanism

An overview of the system is presented in Figure 6.1. The exposed surface area -the one with which a user gets in touch- is a a non-expandable inflatable balloon, composed of two layers: an internal airbag made by folding a polyethylene film (thickness, 0.05 mm); an outer layer made of a commercially available latex balloon, which protects the airbag and create a smoother spherical surface (Figure 6.2). The non-expandable balloon is then connected to a metal tube, which connects it to the mechanism that changes the size and rigidity. In between, an air-pressure sensor (CKD, PPE-P01A-H6) is used to register the changes in the internal pressure of the balloon.

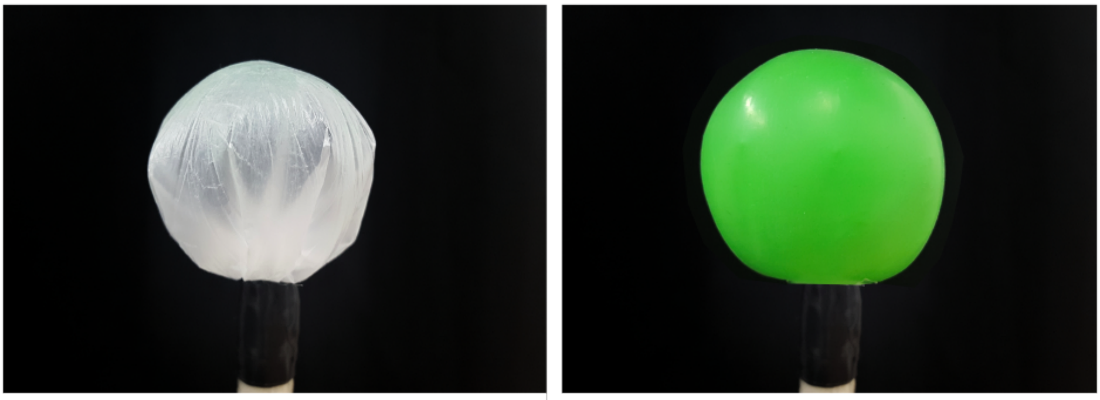

Fig. 6.2. The configuration of the non-expandable balloon. On the left, the internal air-bag; on the right, the external cover.

The mechanism of size control (Figure 6.3) consists of a linear actuator (ELCM2F10K, by Oriental Motor Co. Ltd.) attached to the aluminum tube that holds the balloon. The actuator pulls the balloon in and out through a trumped-shaped tube, which enables us to control the exposed surface area of the balloon (Figure). By doing so, the volume of the balloon matches its exposed area. This mechanism allows the possibility to present no surface at all, by completely retracting the balloon inside the tube. Moreover, the balloon does not need to be completely deflated to reduce its size for pulling it back into the tube.

The mechanism of rigidity control (Figure 6.4) is composed of an air cylinder connected to another linear actuator (ELCM2F10K, by Oriental Motor Co. Ltd.). By varying the position of the piston attached to the air cylinder the internal pressure of the balloon varies according to Hooks Law. Through this setup, it is possible to

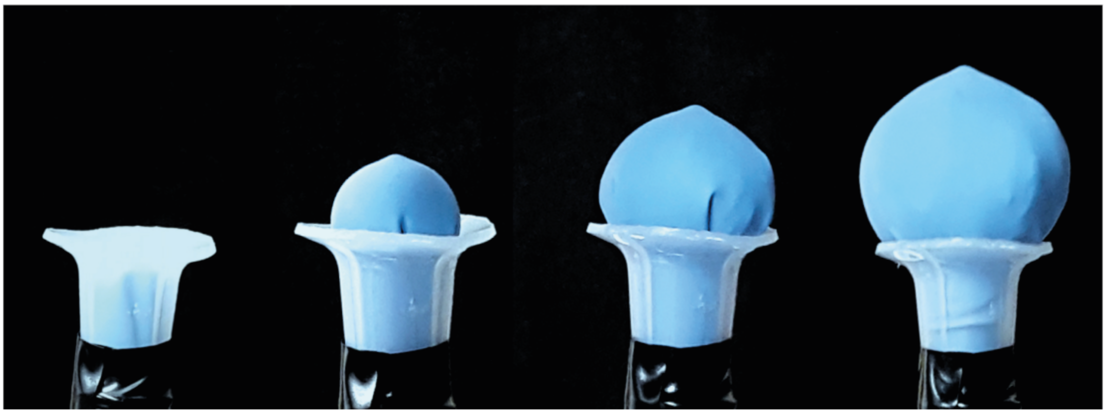

Fig. 6.3. Four variations of size that can be presented by the system: null, small, medium, and large. The size is measured vertically, starting from the base of the trumpet-shaped tube. Except the null condition (size = 0), the other sizes corresponds to 10 mm, 20 mm, and 30 mm.

present a soft surface when the internal pressure of the balloon is low, and a hard surface when the pressure is high.

The sensor and the drivers for the linear actuators are then connected to the DeviceArtToolkit (DATK) from ArcDevice[1], a PIC based microcontroller used to communicate to a laptop computer through a USB bus. The control software was developed using C++, on a Windows machine.

6.1.2 Characterization of Device Properties

In order to accurately presents the stimuli required for the experiment (expressed as rigidity and size), we characterized a) the reaction forces applied on the balloon in relation with three target rigidity value and three target size values, b) the relationship between the movement of the linear actuator and the exposed surface of the balloon.

[1]http://arcdevice.com/products/DATK/DATK.html

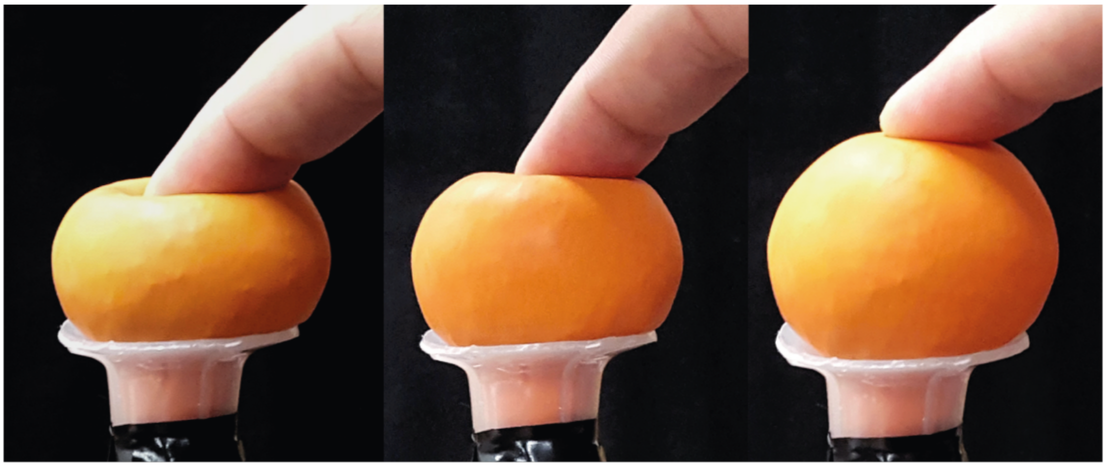

Fig. 6.4. Computationally controlled balloons with variable rigidity and size. (Top) Three possible rigidities that can be presented by the system: soft, medium, and stiff. The internal pressure of each condition corresponds to 7 kPa, 15 kPa, and 22 kPa.

To characterize the reaction forces applied on the balloon, we used a fingertip-like probe, composed of a force gauge attached to a linear actuator (6.5). The probe is placed on the top of the balloon. The force sensor measures every 1 mm the displacement of the probe moving towards the balloon. The relationship between the indentation of the probe and the reaction force on the probe is shown in Figure 6.6. We can observe that the larger the diameter of the balloon, the smaller its maximum internal pressure and more reaction force is registered by the probe. From these results, we confirm that the system can control the reaction force on the users fingertips by controlling the internal pressure of the balloon.

To characterize the change of size, the exposed vertical size of the balloon was measured while changing the position of the rod of the linear actuator at intervals of 5 mm. The internal pressure of the balloon was set to 7 kPa. We found hysteresis between the movement of the linear actuator and the volume of the balloon, when

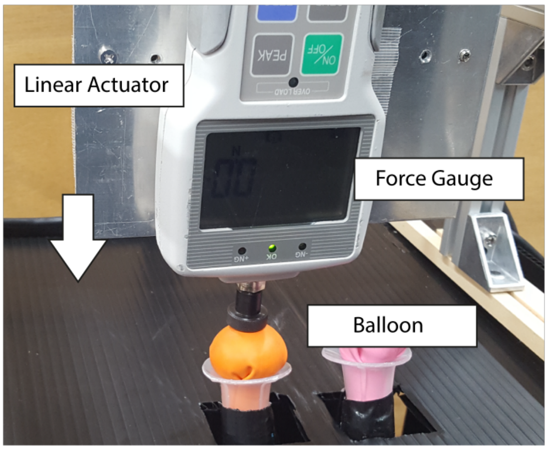

Fig. 6.5. The apparatus used for measuring the reaction forces applied on a balloon.

this was taken in and out of the tube (Figure 6.7). This must be considered while implementing the system.

6.2 Psychophysical Experiment: Perception of Size and Rigidity

6.2.1 Subjects

Twenty healthy subjects participated in the experiment, eighteen males, and two females, aged between 22 and 36. Three were left-handed, and seventeen were right-handed. Subjects were recruited using a mailing list, and they all agreed to volunteer for the experiment.

6.2.2 Procedure

The experiment consisted of two sessions, one dedicated to studying the human haptic perception of changes of rigidity, and a second for the changes of size. To avoid possible order effects, the order of how these sessions were presented to subjects has been counterbalanced for each subject. The two sessions were divided into three

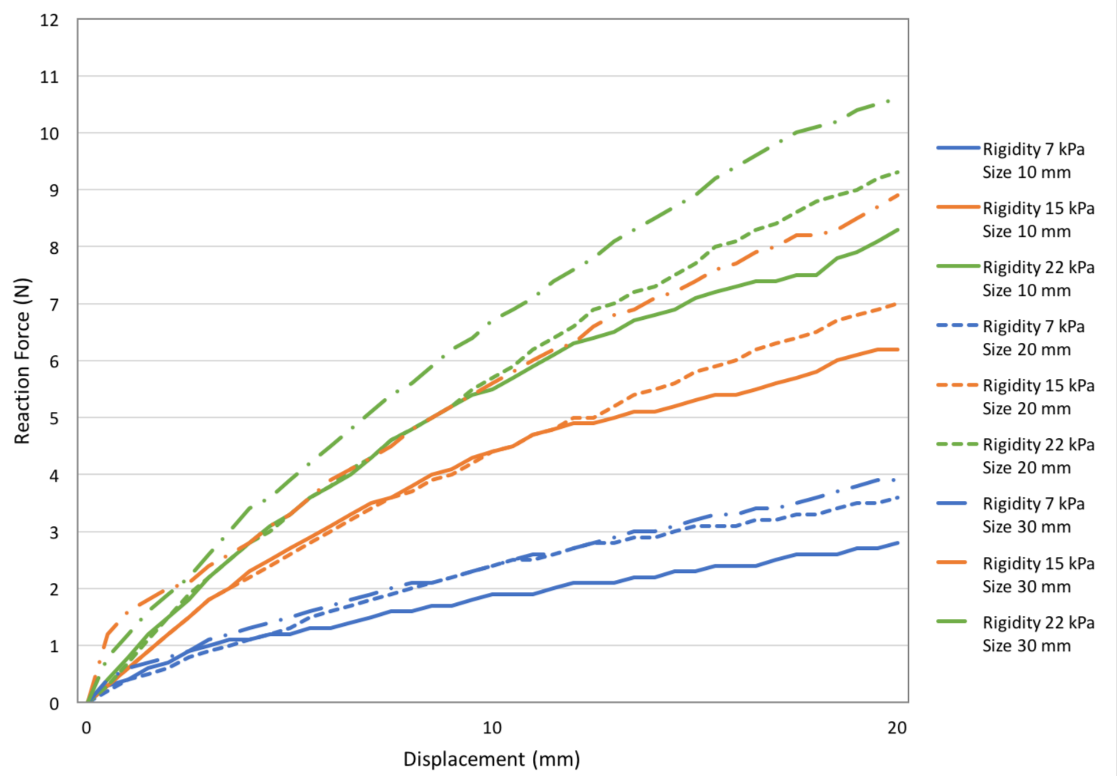

Fig. 6.6. Relationship between indentation and reaction force applied by the balloon on the fingertip-like probe. Three conditions for both size and rigidity were measured using a force gauge.

parts, corresponding to three conditions. Each condition consisted of a two-alternative force-choice discrimination task. In each task, subjects were presented with two stimuli, a reference stimulus with fixed rigidity or size, and a test stimulus with variable characteristics. For the discrimination of rigidity, three standard stimuli were chosen to describe the three main ranges of possible rigidities, such as soft (3-10 kPa), medium (10-18 k), stiff (18-30 kPa). Such stimuli correspond to three conditions of 7 kPa, 15 kPa, and 22 kPa. For discrimination of size, the three conditions correspond to 10 mm, 20 mm, and 30 mm. Similarly, to the ones of rigidity, such conditions fall into the three ranges of sizes that our interface can represent: small (1-10 mm), medium (10-20 mm), and large (30-40 mm). To avoid possible errors of anticipation and

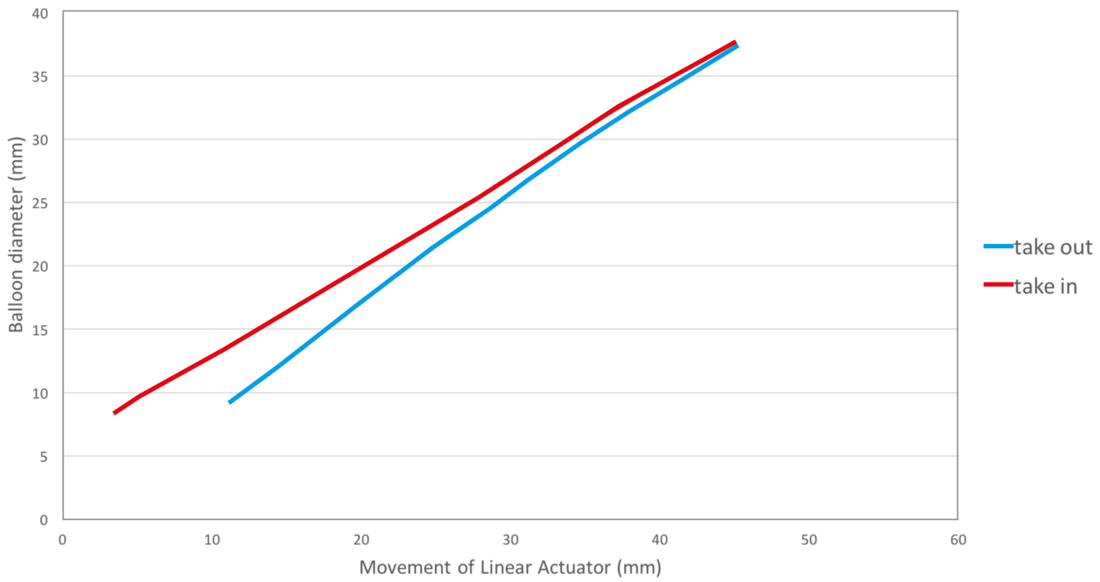

Fig. 6.7. Relationship between the movement of a linear actuator connected to the trumpet-shaped tube, and balloon diameter. The rigidity value used to measure the change of size is 7 kPa.

habituation, the sequence of how the three conditions were presented was randomized between each subject. Also, the three values for size were randomized for the session on rigidity perception; conversely the values for rigidity were randomized for the session on size.

A one-up-one-down staircase procedure was used to estimate the thresholds. Whenever a subject chose the reference stimulus as the larger or the stiffer, the test stimulus in the next trial was a presented one step down. Conversely, whenever the test stimulus was chosen as smaller or softer, the next trial was a small step up. When a subject reported a change, a reversal was recorded. The step corresponded to 1 kPa for rigidity, and 1 mm for size. For each task, there were two staircase procedures: one starting from the high end of the reference stimulus range, while the other starting from the low end. To prevent order errors, the staircase procedures were interleaved. To minimize errors of habituation and anticipation, the presentation order of the test

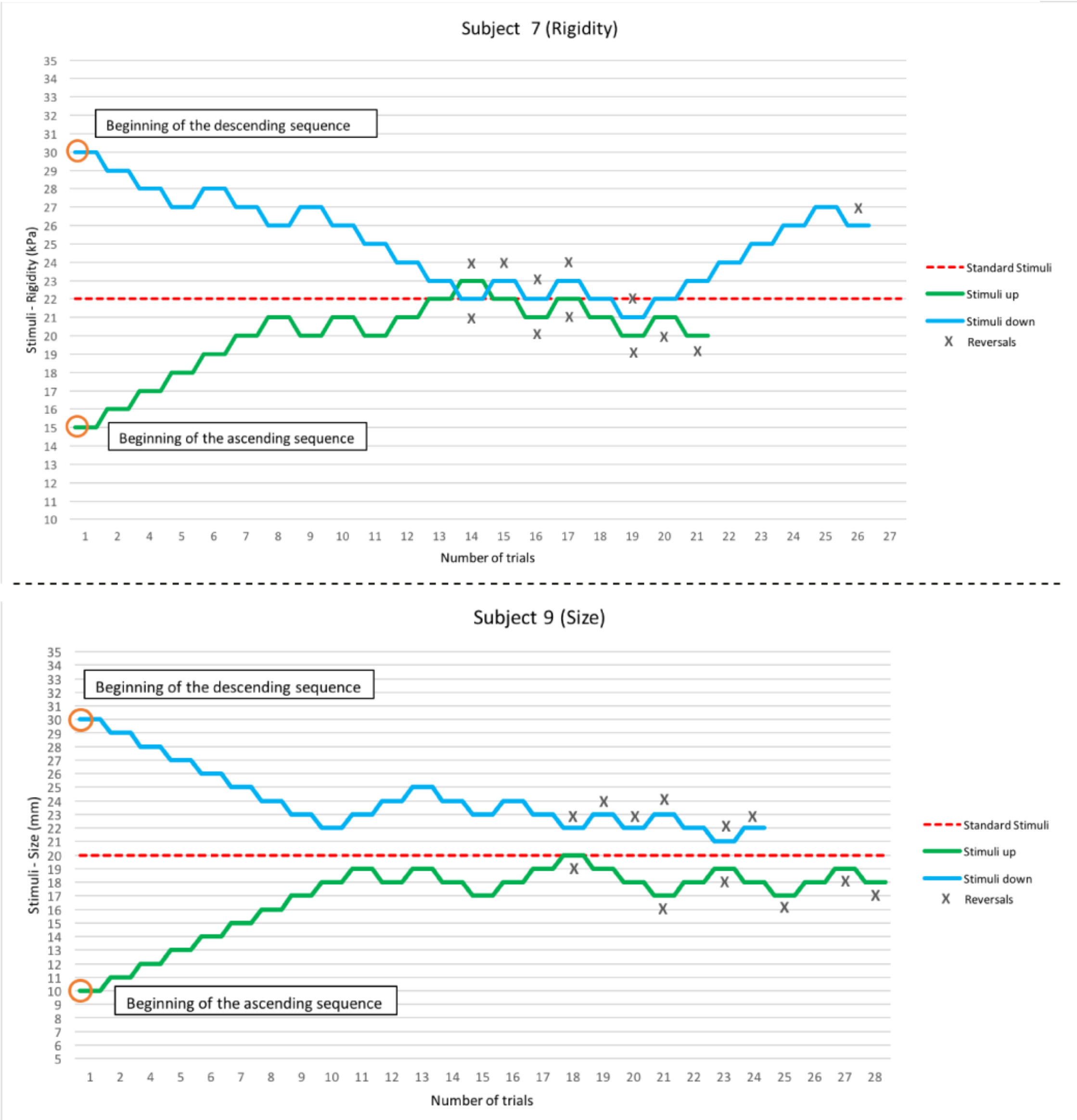

Fig. 6.8. Two examples of the plotted results of two representative subjects. The top figure shows the performance of subject no. 7 for rigidity, condition stiff, 22 kPa. On the bottom, the performance of subject no. 9 for size, condition medium, 20 mm.

and reference stimuli were also randomized for each trial. The number of trails varied since the procedure adapts to the performance of each subject. For all sequences, the experiment continued until ten reversals were collected (Figure 6.8). For both sessions, each subject had to perform six sequences (two for each condition), and sixty reversals were collected in total.

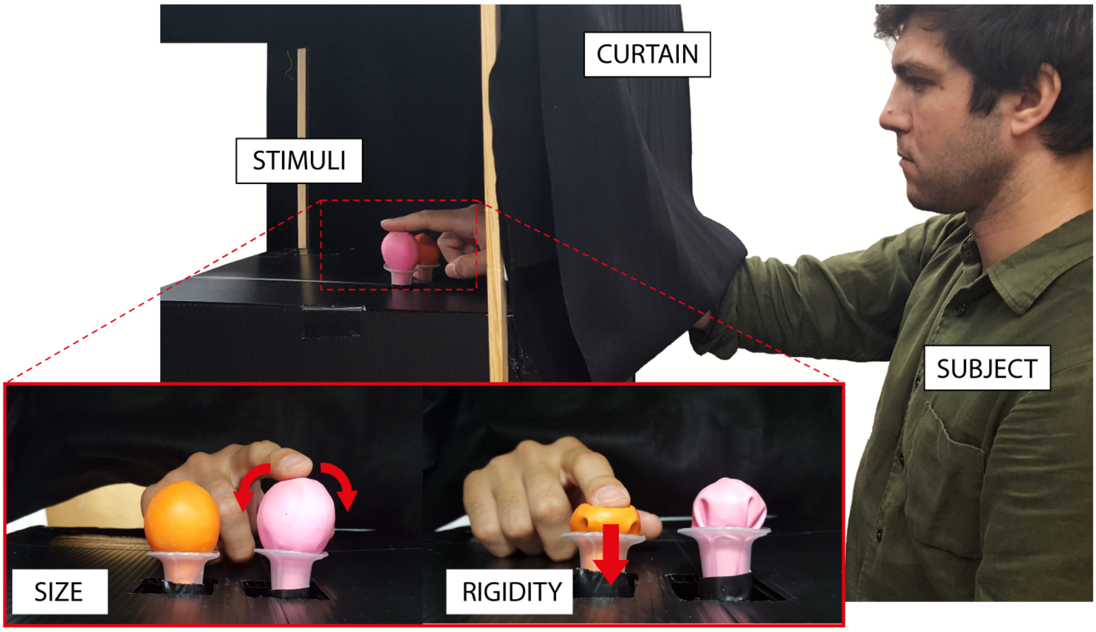

Fig. 6.9. The experimental apparatus used in the psychophysical experiment. A subject interacts with the two stimulus, placed behind a curtain. The two exploratory procedures used in the assessment of size and rigidity are presented.

In each session, subjects sat on a chair facing the apparatus. The setup, as pictured in Figure 6.9, consists of two stimuli placed side by side and surrounded by a curtain. Therefore, subjects could only perceive them through tactile sense only. For each session, subjects were asked first to touch the standard stimuli, perform the requested action with their index finger, and then perform the same action on the variable stimuli, and finally, make a guess.

For rigidity, the subjects were asked to press down the balloons with their index finger. For size, subjects had to trace the contour of the balloon with the same finger.

The role of the experimenter was to guide the subjects, record their answers, and operate the system through a command line interface on a laptop computer running the control software.

Each participant could choose if taking the two sessions together or separately before the experiment. Twelve subjects choose to take the whole experiment, while eight choose to complete the experiment in two separate sessions. Between each session, a short break of 15 minutes was available upon request. At the beginning of the experiment, subjects were introduced to the tasks they had to perform. A brief training session of approximately five-minutes was provided to make subjects comfortable and assure that the task was adequately understood. The experiment for rigidity perception took a total average of 45 minutes to be completed by a subject in all the conditions. For size, the total average time needed was 75 minutes.

6.2.3 Data Analysis and Results

We collected a total average of 125 trials (average) per subject for the experiment on rigidity perception, and 158 trials for the one on size. For each subject and each condition, we plotted the collected data for both the ascending and descending sequences and the corresponding value of each reversal. Out of the ten reversals collected for each ascending and descending sequence, the first four reversals were not included in the final analysis, because the stimulus level has not yet converged near the threshold level. The Upper and Lower Differential Limen were then computed. These values have been used to calculate the PSE for both experiments using the following formula:

$$PSE = \frac{\text{Upper Diff Limen} + \text{ Lower Diff Limen}}{2} \tag{6.1}$$

We then compared the different PSE to confirm if users correctly discriminated the three conditions. We performed a Two-Way ANOVA (1 factor, three levels, within subjects) was used, with Multisample Sphericity Test and Epsilons, and with a Sequentially Rejective Bonferroni Procedure for post analysis. The results are summarized in Figure 6.10.

Then, the JND (Figure 6.11) for each subject and condition was computed using:

$$JND = \frac{\text{Upper PSE} - \text{Lower PSE}}{2} \tag{6.2}$$

Lastly, the corresponding WF was calculated with the following formula:

$$WF = \frac{JND}{PSE} \tag{6.3}$$

The WF for each condition is summarized in Figure 6.12.

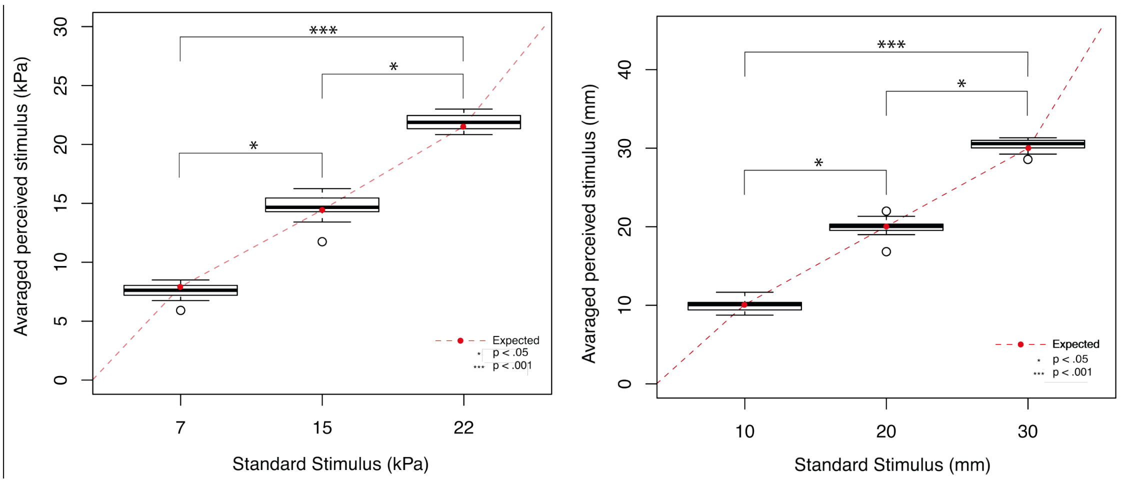

Fig. 6.10. The distribution of the Point of Subjective Equality for all subjects, in relation to the three reference conditions. On the left, the PSE for rigidity, on the right the PSE for size.

The total average PSE for rigidity was: 7.5 for the soft condition, 14.6 for medium, and 21.9 for stiff condition. These values show a deviation from the reference stimuli of +0.5, -0.3, and -0.06 in respect to the three conditions. Regarding size, the total average PSE were: small condition = 10.06, medium = 19.9, and large = 30.4, with a corresponding deviation from the reference of +0.06, -0.1, and +0.4 respectively. The results of the Sphericity Test on the PSE values for both size and rigidity reported a p

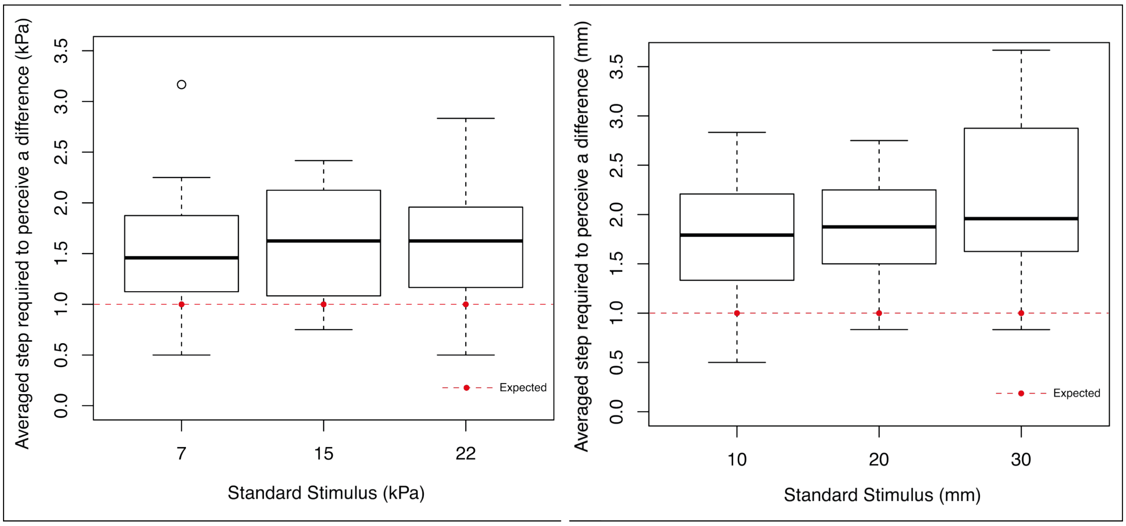

Fig. 6.11. The resulting Just-Noticeable Difference for all subjects, in relation to the three reference conditions. On the left, the JND for rigidity, on the right the JND for size.

STANDARD STIMULUS	RIGIDITY (kPa)			SIZE (mm)		
	7	15	22	10	20	30
Weber Fraction (average)	0.21	0.09	0.07	0.17	0.09	0.07

Fig. 6.12. Results of the psychophysical experiment. The total average Weber Fractions for each condition are reported, together with the global WF for both rigidity and size.

$< .001$, and the post-analysis reported $p < .05$ between each condition. For the JND, the total average was 1.52 soft, 1.49 medium, and 1.62 stiff, for rigidity. While for the experiment on size perception the JND values correspond to 1.78 for small, 1.94 for medium, and 2.14 for large. The total average WF for size were: small = 0.17, medium = 0.09, large = 0.07. The results from the experiment on rigidity perception were 0.21 for soft, 0.09 for medium, and 0.07 for the stiff condition.

The results of the statistical test conducted on the PSE values provide an important ground for confirming our hypothesis. Therefore we can say that the interface can represent three different conditions (of both rigidity and size), which can be correctly distinguished by humans' touch. By looking at the values of both experiments, we can notice a small deviation of the PSE values from the ones of reference stimuli. If we consider the performance of each subject, the third condition for both size and rigidity appear to be the most uniform. This may reveal that subjects can identify better stiffer and larger surfaces. The second metric presented in the study is the Just-Noticeable Difference, which contributes to the understanding of how precise subjects perceive the stimulus. The results for rigidity appear to be in line with ones reported in literature [90, 104]. However, such works underline that perception of rigidity involves not only touch but a much complex interplay of sensory information. Tan et al. [90] noticed that the presence of force-feedback could influence the perception of compliant objects resulting in larger JND values. This may justify our results since our system provides reaction forces at the fingertip when the surface is indented. A future study that compares the two conditions - one with reaction forces and one without - can elucidate better this aspect and reveal which relation exists between force cues and the perception of rigidity. Other studies [91, 105, 106] showed that the presence of visual stimuli could also influence the perception of rigidity by enhancing the subjects sensitivity. Such aspects must be considered for integrating such interface with a VR environment [107]. Regarding the perception of size, the values follow the ones presented in the literature. For instances, Durlach et al. [108] showed that JND values increase with the increment of the reference length. The Weber Fractions can provide additional information to better clarify our results. As for the PSE and JND values, also the Weber Fractions found in our experiments are consistent with the ones reported in other literature (i.e. [109]). For size, the values follow what observed by Gaydos [96]: the fractions for small stimuli are larger than the ones for large stimuli. However, it was noted that the shape of the stimuli might influence the perception of size. Kahrimanovic et al. [97] reported that spherical objects do not follow such behavior. Such difference can be explained by the different exploration technique used in the two experiments. We used finger tracing of the stimuli, which can provide more detailed information, while they used hand enclosure, which can generate mainly rough information about size [88]. For rigidity, the total average Weber Fraction of all conditions is similar to the values generated by previous work on haptic perception compliant objects [93,110]. We may confirm that the balloons used in the experiment are perceived as a compliant material. However, our hypothesis specifies that the proposed haptic interface can produce variable rigidities between soft and stiff. Tan et al. [111] found a WF of 0.22 corresponding to soft surfaces, which is similar to the value reported for the first condition. Blair and Coppen [112] reported a WF of 0.13 for a rubber stimulus, which is also very closed the one reported in our experiment for the medium condition. We can also observe that the WF for the third condition is coherent to the ones reported by previous studies which found a WF < 0.08 for stiff surfaces [111,113]. Based on these comparisons, we can confirm that the proposed system can represent different rigidities and sizes that are correctly distinguished by tactile sense. Moreover, we might argue that the three conditions for both rigidity and size are perceived by human touch similarly to materials and objects with similar characteristics. This suggests that our haptic shape-changing interface can be used to present physical characteristics of virtual objects to users that might be perceived similarly to the ones of real objects. The psychophysical metrics -together with the technical assessment of the system- reported in this study, provide valuable information for integrating haptic shape-changing interface with virtual environments. From these results, we can devise several approaches on how the proposed interface can present size and rigidity of virtual objects (Figure).

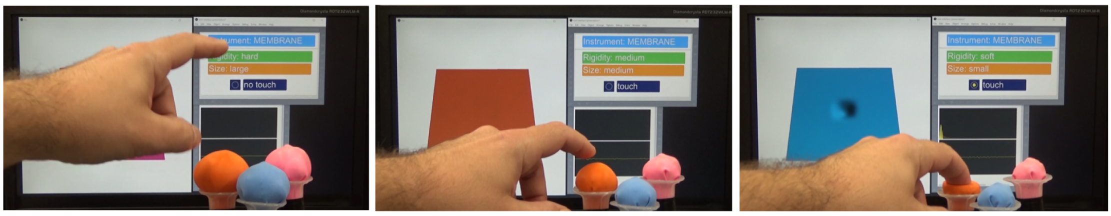

Fig. 6.13. A user interacts with three virtual surfaces having three different physical characteristics: (top) large size and stiff rigidity, (middle) medium size and medium rigidity, (bottom) small size and soft rigidity. The contact between users finger and the haptic interface is recognized by the system.

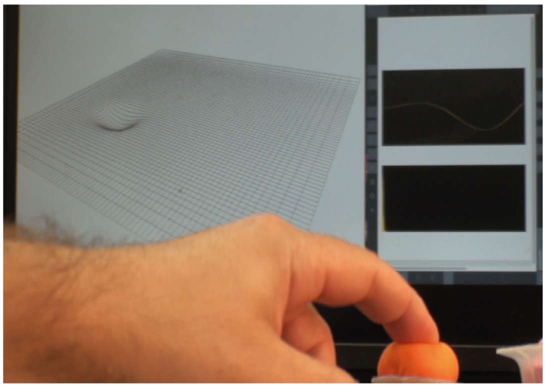

Fig. 6.14. A user interacts with a virtual surface by indenting the haptic interface. The visual representations shows a small contact area and exhibit a medium type of rigidity, which is also presented through the interface.

6.3 Proof-of-concept System

Besides the understanding of the tactile qualities of the Volflex system, it is equally important to develop a framework for presenting virtual objects physically, as well as making the system capable of accepting and interpreting direct touch input. In this section, we present a proof-of-concept application by outlining its main elements and discuss its implications in the context of malleable media.

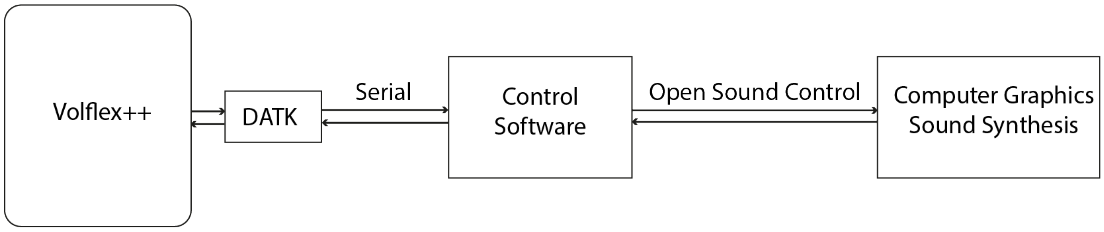

Fig. 6.15. A schematic representation of the proof-of-concept system.

6.3.1 Presenting Virtual Objects through their Size and Rigidity

One of the open design challenges is the mapping of characteristics such as size and rigidity of a virtual object (usually presented through computer graphics and sound synthesis) to the physical controls of the shape-changing interface.

The process of mapping digital content to shape-changing interfaces is drastically different from the one used for haptic interfaces. When the goal of an interface is to render reaction forces, the virtual object and the haptic interface do not have to be topologically consistent. It also differs with the mapping used in many shape-changing interfaces. For instances, pin-array interfaces use a compelling metaphor for presenting virtual surfaces: each pin is the physical counterpart of a digital pixel. Then, the brightness of each pixel can be mapped to the vertical displacement of the pins. Such mapping is not suitable for an interface composed of spherical units like Volflex++. In order to find a possible solution, we investigated two possibilities for mapping size and rigidity of virtual objects to the physical surface created by the balloons of Volflex++. First, we looked at flat surfaces, and second at volumetric surfaces.

If only a flat surface has to be presented, NURBS can be used. In this case, the size of each balloon can be mapped to the control points of the virtual surface, and used to represent the contact area: larger the balloon, larger the contact area visible (Figure 6.16).

The rigidity is then mapped to the vertical displacement of the surface. When indented, the surface deforms in the area that corresponds to the position of the balloon being touched. If the contact area is large, the displacement takes a wider area. Thus, the magnitude of the displacement depends on the rigidity of the balloon.
On the other hand, if volumetric objects have to be presented, other computer graphics techniques must be considered. Metaballs [114] can facilitate the representation of arbitrary virtual objects based on an array of spherical surfaces (Figure 6.17). Such a technique can also help to better localize the position in the virtual space of each balloon, present a change in size as a change in volume. Then, it can also to visually fill the spaces between each balloon since a continuous surface can be rendered on a Head-Mounted Display or through a projection. Lastly, since our interface can also present a null volume, virtual objects with holes and cuts can be presented using the combination of such techniques.

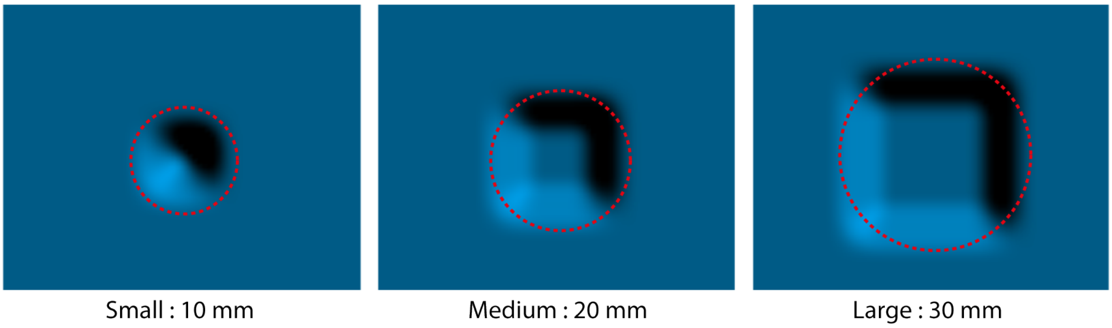

Fig. 6.16. An illustration of three possible representations of size on a flat surface.

The rigidity is then mapped to the vertical displacement of the surface. When an indented, the surface deforms in the area that corresponds to the position of the balloon being touched. If the contact area is large, the displacement takes a wider area. Thus, the magnitude of the displacement depends on the rigidity of

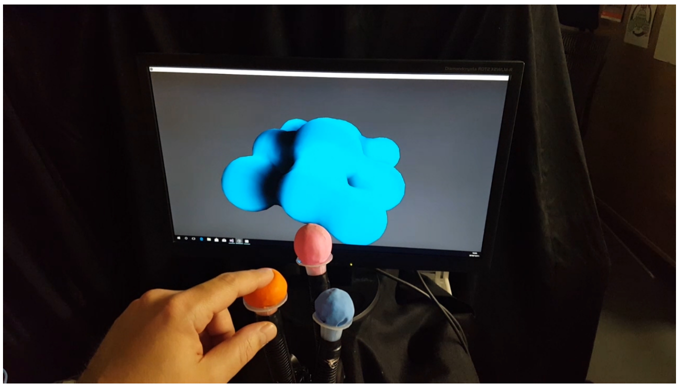

Fig. 6.17. An illustration of using metaballs to present volumetric shapes.

the balloon. On the other hand, if volumetric objects have to be presented, other computer graphics techniques must be considered. Metaballs [114] can facilitate the representation of arbitrary virtual objects based on an array of spherical surfaces. Such technique can also help to better localize the position in the virtual space of each balloon, present a change in size as a change in volume. Then, it can also to visually fill the spaces between each balloon since a continuous surface can be rendered on a Head-Mounted Display or through a projection. Lastly, since our interface can also present a null volume, virtual objects with holes and cuts can be presented using the combination of such techniques.

6.3.2 Dynamic Touch Detector

Even if every balloon is equipped with an air pressure sensor, this has not to be used to detect user's input that can be used to interact with the content displayed by the Voflex++ system. For this, we implement a dynamic touch detector using the air-pressure sensor. We call it dynamic because the Volflex++ system can present various types of rigidities and sizes, in a range from 0-30 kPa, and 0-40 mm respectively. For this, we had to implement a touch detector capable of adapting to various internal pressures and sizes. The goal of such system is to discriminate both touch (when a finger gets in contact with the surface of the balloon) and the amount of

pressure applied after the contact is detected.
Every time a new target rigidity is detected, a short sample of the variation of the internal pressure is recorded. These values are then averaged, a mean is derived, and an offset is applied depending on the size (more the diameter is larger more the offset is larger). The resulting value determines a threshold. In parallel, the internal air pressure is continuously compared with the threshold value. When the current pressure is detected as greater than the threshold, a touch event is recorded. When a new change in the target rigidity is detected, the touch detector is disabled until the rigidity is reached. In parallel, depending on the current rigidity, the magnitude of the pressure applied by the finger is computed in real-time. Finally, the touch detector provides a touch message composed of contact detection and its relative pressure. An example of the use of the touch detector is showed in Figure 6.18.

Additionally, to the software-based touch detector, we developed a hardware touch detector, based on capacitive sensing [115]. A thin layer of conductive ink (Bare Conductive) is applied on the surface of the internal air-bag (Figure 6.19). The resulting electrode is connected to an Arduino board. Compared to the software based touch detector, this approach does not require to determine a threshold and can detect touch more accurately also when no pressure is applied. Also, since the electrode is compliant with the surface of the balloon, it is independent from which size or pressure the balloon has. However, this method will increase the complexity of the system. Despite the interesting possibilities offered by the capacitive sensing balloon, the current implementation is not very stable. This is why we opted for the software-based touch detector.

6.3.3 Physical Sound Model of a Membrane

We developed a physical sound model that mimics the behavior of a membrane, like the one of a drum. As a membrane, the sound depends on how large and thick the

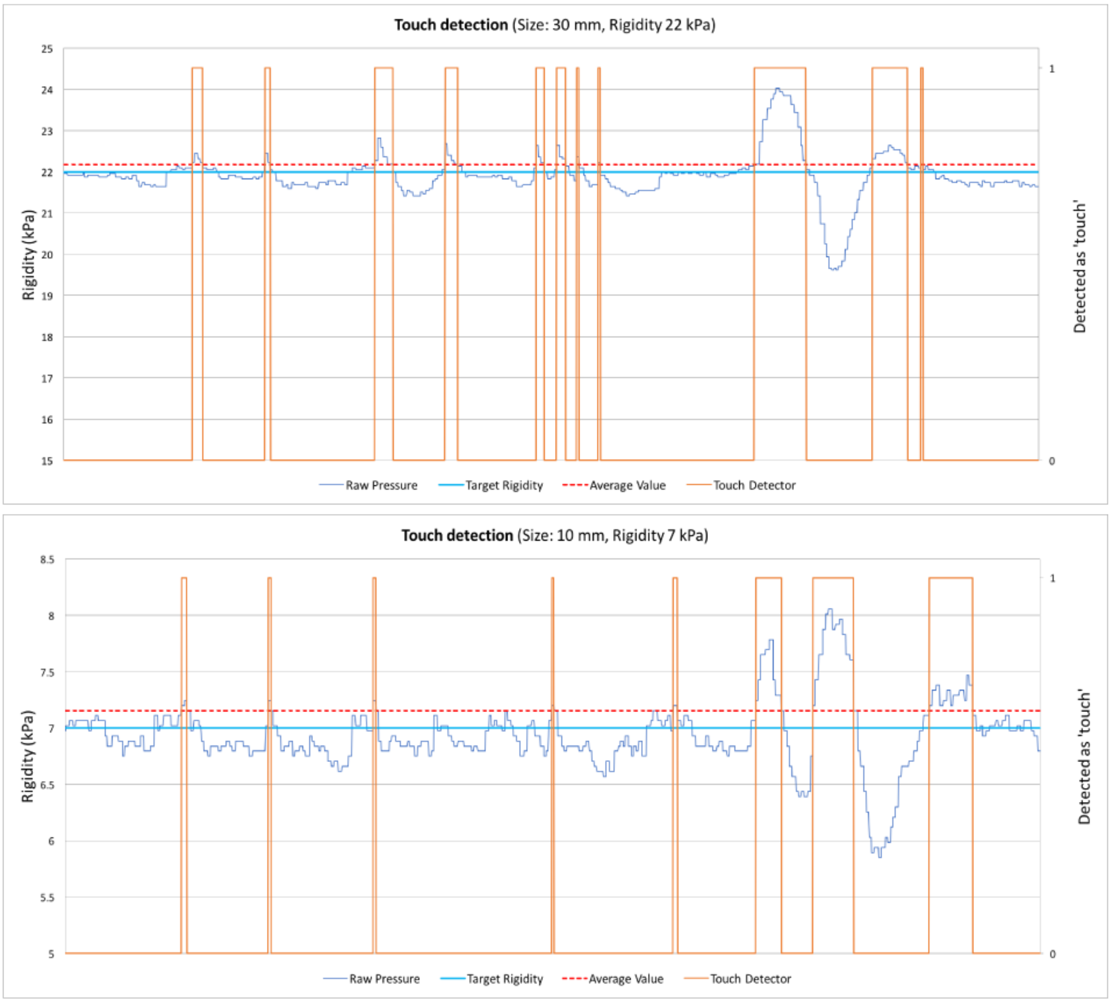

Fig. 6.18. Two recordings of the dynamic touch detector.

membrane is, and how much the membrane is stretched. More the tension increases more the pitch increases. A schematic representation of the model is presented in Figure 6.20. The proposed sound model is a hybrid combination of a Frequency Responsive Filter and a Mass-Spring Model, developed using Max/MSP-Jitter. A hybrid model is needed because -similarly to the touch detector- the system can present a wide variety of rigidities and sizes. Consequently, the sound model has to be flexible enough to adapt to different input parameters. As every physical model,

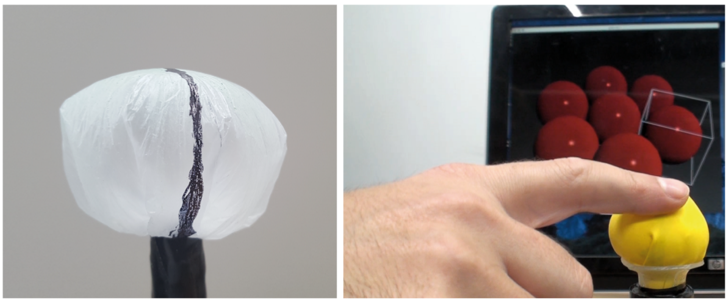

Fig. 6.19. The implementation of the capacitive touch sensor. On the left, the internal air-bag; on the right, a test with a 3d simulation.

the sound source has to be provided with an excitation signal. This is provided by the touch and pressure magnitude messages produced by the touch detector.

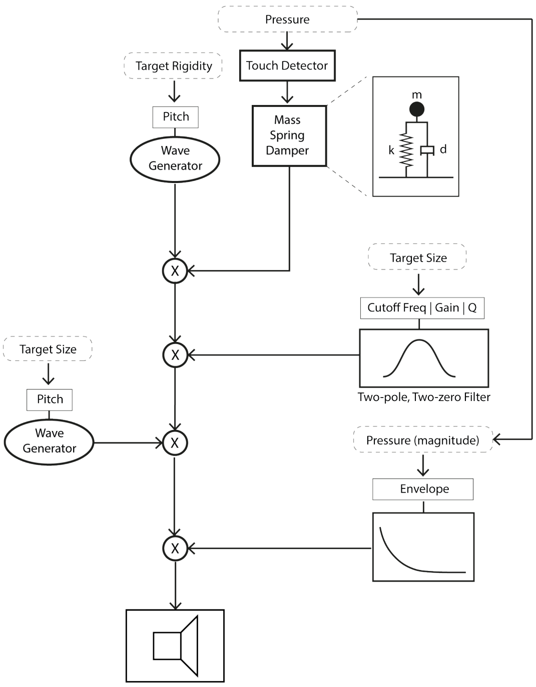

Fig. 6.20. Schematic representation of the sound physical model.

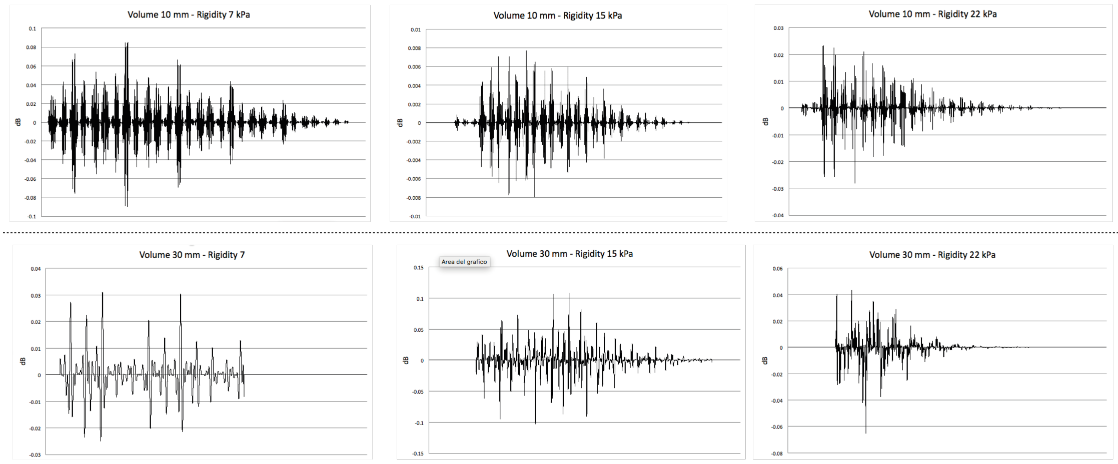

Fig. 6.21. Two examples of the sound generated by a touch event. On the top, a sound generated with three different rigidities on a volume of 10 mm. On the bottom, a sound generated with three different rigidities on a volume of 30 mm.

6.3.4 Model-based Shape-change

Since a Shape-changing Interface can represent variable physical properties (in this case, rigidity and size) we need a strategy for both visual and the sonic components of the virtual objects that continually adapts to the changes. Since Volflex++ is composed of inflatable balloons, elastic objects with variable rigidity and size can be presented. As the results of our experiments suggest, Volflex++ may render physically materials that range from soft to stiff. Elastic objects can be represented, both through computer graphics and sound synthesis, using physical models based on mass-spring systems [116,117]. The elasticity of the material is usually expressed with a value k, which specify the amount of the deformation of the virtual object in response to a pressure applied on its surface. Using the results of the experiment reported in Figure 6.6, we performed an estimation of the possible k values corresponding to each rigidity condition. The results are: k = 388 for soft, k = 714 for middle, and k = 1220 for stiff. Such values roughly correspond to the ones measured on objects made of foam or silicone, for the soft and middle conditions, while the value of the third condition is more closed to the coefficient of a metal spring. Using this additional information we can find the most suitable mapping between all the possible representations of the virtual objects, being visual, auditory, and haptic. For instances, a rubber-like virtual object can exhibit the same amount of deformation and resistance to user's contact not only through visual feedback, but also through the sound generated by the direct touch contact, and through the haptic interface. All three elements will then follow the same behavior, established by the qualities of the material selected. Moreover, by combining several balloons, more dense and articulated shapes can be presented. By using this method, we can create shape-changing interfaces that coherently display the visual, tactile, and sonic properties of virtual objects. Moreover, what the user can experience is not a series of forces generated by contact, but a material that blurs the boundaries between physical and virtual materials.

6.4 Conclusion

In this chapter, we presented the implementation of the Volflex++ mechanism for presenting the size and rigidity of a virtual object physically. Regarding the technical aspects, there are several open challenges. First, to make the system more portable, the proposed method must be simplified and scaled down. Second, the non-expandable balloons must be fabricated more efficiently, since they tend to exhibit cracks or break after prolonged use. Third, in order to achieve a fully shape-changing interface, the position of each balloon must also be controllable in three dimensions. This will require the use of other actuators to enable such changes, and a sensing system to correctly present the position of the balloons in a virtual space. Future works will try to tackle such issues. Through this chapter, we also showed that for developing haptic shape-changing interface it's equally important to develop a technique that can present virtual materials physically and an understanding of the human tactile perception of objects' properties such as size and rigidity. We showed how different sizes and rigidities could be presented through an array of computer-controlled air balloons, which can be directly manipulated by users. We provided an evaluation of both mechanisms, one for changing the rigidity, and one for changing the size of a balloon. We then described the methods and procedures used in a series of psychophysical experiments aimed to confirm that human subjects can distinguish several types of rigidities and sizes. The corresponding Point of Subjective Equality, Just-Noticeable Difference, and Weber Fraction were provided and then compared with values found in previous research on haptic perception. Our results suggest that the proposed interface can effectively present the physical characteristics of objects that are distinguishable by humans. Lastly, we discussed the implications of our findings to guide the design of a proof-of-concept system. We show how the proposed this haptic shape-changing interface can be used to present a coherent virtual environment were visual, sonic, and tactile feedback are orchestrated together and based on shared physical properties.

7. DISCUSSION

In this chapter, we discuss the results we gathered about the process of design, implementation, and evaluations of the two systems Vital+Morph and Volflex++. Through this discussion, we also outline the main characteristics of Malleable Media, show how our work contributes to the field of media art, and how our approach differs from the ones of Human-Computer Interaction.

7.1 Design Guidelines

7.1.1 Physical Presence of the abstract

With Vital+Morph we showed that when an object becomes enhanced with real-time data (in this case biomedical), it can serve as a strong representation of the distant other. Previous studies of Janssen et al. [118] revealed that sharing physiological signals can facilitate and promote connectedness by making distant people feel closer. It seems that a person tends to interpret a shared physiological signal as a surrogate, or an abstraction of the other person. A single signal can become a representation of an entire absent body, and then report that the distant person is felt physically closer. Such suggestion can be connected to a phenomenon of presence-in-absence described by Garns et al. [119], which is as a subjective feeling of a significant other when he or she is not physically co-present, and several emerging technologies increasingly aim to support this feeling of presence. Moreover, Slovak and Fitzpatrick [120] noticed that a similar phenomenon could be compared to the one triggered by physical tokens of loved ones that people keep close as a reminder of a distant person. Researchers in HCI noticed that the use of tangible objects as physical surrogates can a powerful, intuitive method of sustaining long-distance relationships [121]. Even though the

Vitals presents an elementary shape, recent research in social robotics [122] opined that even a device with a very simple and almost abstract appearance can be a compelling factor for conveying a sense of physical presence. In the case of Volflex++, we proposed several ways to map the rigidity, size, and spatial arrangement of a virtual object to the physical characteristics of the interface. Materials qualities are an important way to establish a relationship between physical and virtual surfaces.

7.1.2 Digital Aliveness

As observed by many comments made by users of Vital+Morph, the association between shape-change and digital data appears to be very powerful. Moreover, having a physical display that exhibits the qualities of a living organism seems to enrich the embodiment of data through shape-change. Several users noticed this. These claims are supported by the literature of shape-changing interfaces that has emphasized the importance of designing life-like movements for conveying meanings [123–125]. While Vital+Morph support animation through a dynamic change of geometry, Volflex++ still lacks this aspect. However, physical animation is not enough. The combination with tactile feedback proved to be fundamental in order to let people experience different characteristics of the data displayed through a shape-changing material.

7.1.3 Active and Passive Touch

The shape-change provided by Vital+Morph can be mostly perceived through passive touch. The material deforms itself in response to digital data and presents characteristics such as frequency and peaks. In this case, the force produced by shape-change is used to generate a haptic perception of digital data. This may suggest that digitally enhanced objects possess an agency that directly affects humans, at least from the tactile sense. On the other hand, in the interaction with materials and surface force is not needed for the perception. When interacting with a material, only fingers displacement and deformation of the surface are needed. For this, the haptic characteristics of Volflex++ can be perceived mostly through active touch. Here, the shape change represents constraints that guide the experience of the user. The surface has to be touched to understand its different qualities if its soft or still if it's large or small. Previous literature regarding shape-changing interfaces has not looked at such differences, and that different types of haptic perceptions can be used for different purposes. We showed through two implementations that different types of haptic perceptions can be provided by shape-change.

7.1.4 Plurality

Our evaluation in the context of a media art exhibition showed that Vitl+Morph was approached by multiple users, and it can supports a social-type of interaction. In this case, we noticed that a system like Vital+Morph could potentially promote remote monitoring as a social activity. This is supported both by the form factor and the modularity of the interface. This is supported by the research on TUIs, where circular tabletop arrangements of digitally augmented objects have shown a high potential to promote collaboration and social inclusion [126], and by shape-changing interfaces such as FEELEX [28] and inForm [49]. Even if we did not provide any formal evaluation of this aspect, we can see that Volflex++ can be used by different people since it can produce volumetric surfaces that dont depend on a display or a head-mounted display, so it is not affected by problems of orientation. Previously, Enzaki et al. [127] showed that multiple people can use a three-dimensional balloon interface at the same time. The works presented in this thesis show that even if the technology or the metaphor used is different, this characteristic is respected and it is relevant. This is a different approach from tool-type and even many examples of encountered-type haptic interfaces, which support only interaction of single users. Since shape-changing interfaces aim to be used and perceived similarly to any other physical surface or object, this characteristic is very important has to be fulfilled.

7.1.5 Biological Metaphors

To guide the design of the systems presented in this thesis we used biological metaphors. As noted by Benyus [80] a bio-inspired metaphor is not used only for aesthetic reasons, but mostly as a way to design a system and to simplify and organize complex relations. In this thesis, we explored two main biological metaphors. Volflex++ use a bio-inspired approach to present objects from a structural point of view. There is a relation between shapes created by an array of balloons and how structures are formed in nature. Architect Frei Otto identified this element as Pneu [77]. This term comes from the Greek word "Pneuma", which means air. According to Otto, Pneus are one of the most efficient technical, structural systems found in nature, and represents the most fundamental structural system of living nature. A pneu is a structural system consisting of a ductile envelope which is capable of supporting tensile stress, is internally pressurized and surrounded by a medium. Pneus have been used by Otto to design structures used to transfer forces but also as an agent for form generation. Pneus are in principle soft when they form a shape, but then they can solidify and become hard like the carapace of a single cell organisms, or animals bones. Using balloons that can change their materiality can allow different types of evolution of hardness, where the global arrangement of pneumatic elements reflects the way how in nature organisms take their shape through different evolutions and mutations. As already explained, for Vital+Morph we looked at a group of biological organisms called diatoms. We referenced such organisms as a way to organizing different data sets to better express the sense of the data, since in the case of Vital+Morph they need to represent a living organism. According to the data we gathered during the exhibitions, the majority of the users understood this aspect and considered it as a fundamental element. Through such examples, we showed how bio-inspired metaphors could be used to design shape-changing interfaces.

7.1.6 Viscerality

The data gathered during the exhibition of Vital+Morph showed that translating abstract data into a physical form make users more likely to question the process of how data get represented. Our results offer an empirical support to the thesis expressed by Deborah Lupton in her essay entitled "*Feeling your data: Touch and making sense of personal digital data*" [128]. Lupton underlines that the most important characteristic of data physicalizations is that when encountered they generate visceral responses from users. We showed how this is especially true with very sensitive measurements such as vital signs. Is it true that we reported some very critical comments from users, and they me be seen as a failure of the design. On the contrary, Lupton said that the presence of a friction between the haptic media, the data it represents, and the users must be viewed as a productive mode for generating knowledge. Essentially this is a process of critique. She noticed that often physical representations of digital data could evoke sensations of discomfort, but such uncomfortable feeling has to be used to awake people from passive acceptance of events and proliferation of digital data and quantified world. Moreover, for Lupton, the primary goal of physicalizations is provoking political responses. However, the considerations proposed by Lupton refers mostly to data sculptures. Through Vital+Morph we expanded the discussion to the use of shape-change. This aspect has been not considered in the evaluation of novel shape-changing interfaces. Moreover, media artists Simon Penny [22] noted that art can be seen as a way to create a world that can help to envision possibilities and criticalities of possible scenarios between humans and technology. This is where we place our work with Vital+Morph. Also, we see our contribution as an addition to the growing variety of alternative data representations. However, Lupton noticed that in terms of user experience we do not know that much about the sensory dimensions of how people interact with data representations, being them either two or three-dimensional, physical or visual [128]. The characterization of the sensory response and perception of materials that represents digital contents is then an open issue. This is why we conducted a psychophysical experiment to characterize such aspects with Volflex++. We hope that this can contribute in creating an awareness of the importance of the sensory response of such systems since their focus is to generate sensations and feelings.

7.2 A New Form of Media Art

We position the overall contribution in the context of Media Art. We believe that the concept of Malleable Media can improve the realization of artworks that can adequately represent virtual and digital contents through shape-change. The focus of media art is the creation of new types of experiences by inventing new types of relations between the digital and the real world. Differently for HCI and computer science, for media artists, the concepts of interface and interaction have a much broader impact, and they have always been questioned, criticized, and pushed further [129]. This sensibility can be dated back to the work of Myron Krueger, where he tried to challenge the dominant concept of the interaction with computers and digital worlds: "*What had always bothered me about computers specifically (...) was that you have to sit down to do it. I wanted my body back! Thus, I always thought of creating an interface that would permit me to move around as I interacted with the computer*" [130]. The work of Krueger anticipated both conceptually and technically the development of gestural interfaces, interactive immersive environments, and contributed equally with computer scientists like Ivan Sutherland to the development of Virtual Reality in terms of both vision andrealization [131]. By analyzing the history of the development of interfaces and interactions we can see a parallel development between computer science, art, engineering, and design.

Media artists have also contributed to finding ways to make virtual and digital content physical. Haptic touch is mostly lacking element, not very successfully integrated with mechanisms of shape change.

7.2.1 Living Sculptures and Deformable Screens

Since the introduction of electro-mechanical devices, artists have tried to use physical movement to augment their creations. This type of art has been defined as "kinetic", and it represents an important stage that led to the development of media art [132]. With the advent of computation, artists have tried to use movement to represents digital events 7.4.

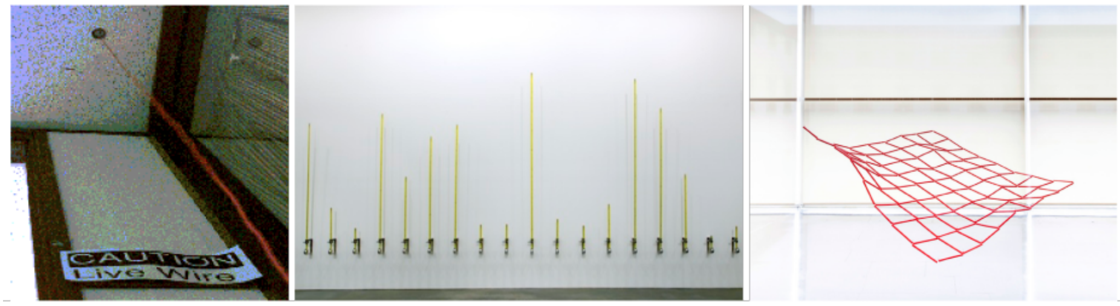

Fig. 7.1. Three media artworks oriented to data physicalization: "Live wire" (left), "Tape Recorders" (center), and "Tele-present Water" (right).

One of the first and more notable examples of this approach was the "Live Wire" created by Natalie Jeremijenko in 1995[1]. The "Live Wire" is a three-dimensional and real-time network traffic indicator. It was used to create a physical manifestation of the digital world. When plugged into a local network, the wire was moving and jiggling according to the amount of internet traffic of that specific location. With "Tele-present Water", the American artist David Bowen pushed this idea further by using shape-change to represent distant events in a tangible form[2]. This installation displays information about the movement of the water into a kinetic sculpture. The information consist of the g-force and acceleration of the surface of a lake were collected by a buoy station. The resulting effect is similar to the one of a virtual

[1] http://tech90s.walkerart.org/nj/transcript/nj_04.html

[2] http://www.dwbowen.com/telepresentwater/

simulation but physical. However, not only environmental data have been used, but also measurements of the human body. Mexican artist Rafael Lozano-Hemmer developed "Tape Recorders"[3], an installation that physicalizes in real-time the amount of time that visitors spend in front of it. This is expressed through a row of motorized measuring tapes which goes up-wards until a person stands in front of them. Even if very compelling and intriguing, such installations do not allow people to touch and interact, but only contemplate them. This results in physical representations that are perceived as visual displays, which impose a distance between a human actor and the content they display.

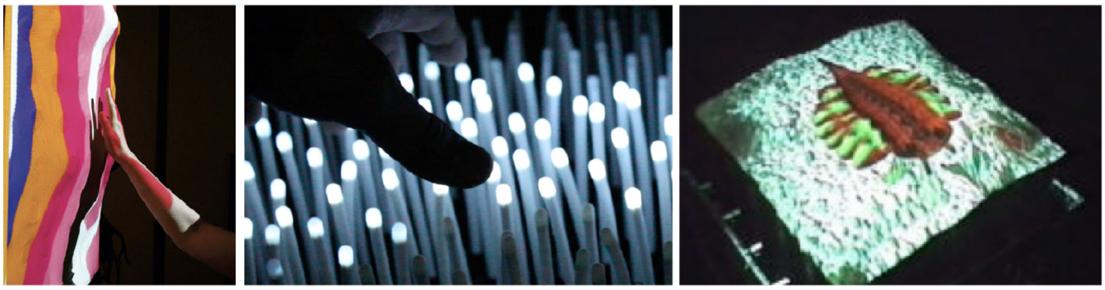

Fig. 7.2. Three interactive media displays: "Gemotion Screen" (left), "Luminescent Tentacle" (center), "ANOMALOCARIS" (right).

To address such limitations, several artists have tried to develop compliant displays that can accept human touch 7.4. This is the case of the "Gemotion Screen", a large vertical interactive display developed by Niiyama et al. [133]. The "Gemotion Screen" enables the display itself to deform by following the behavior of the computer graphics displayed on it. Another example that follows a similar concept is the installation "ANOMALOCARIS", which is based on the FEELEX system [28]. According to the artists, the goal of such works is to express emotions through physical movement, and adding a haptic dimension to visual contents. Similarly, media artist Akira Nakayasu has worked for a long time on bio-inspired shape-changing displays. One of this is

[3]http://www.lozano-hemmer.com/tape_recorders.php

"Luminescent Tentacle" [134], which is inspired by the behavior of the tentacles of sea anemones. A fluid simulation drives the movement of the tentacles and a soundscape, which can be modified by the users hand movement. Both "Gemotion Screen" and "Luminescent Tentacle" show that shape-change can be used for expressing emotions and providing novel experiences of immersion to people. However, even if they can be touched, there is no direct physical interaction between a user and the system.

Through "Vital+Morph" we showed that the power of dynamic physicalizations is revealed when they are directly explored and held by users. Through "Voflex++" we showed how the role of materials and changeable materiality is an important element for creating haptic interactions, and that movement and simple changes of shape (like a vertical displacement, as showed by "Measuring Tape" and "Gemotion Screen") is not the only important element to create a successful experience.

7.2.2 Haptic Media Art

Until now we looked at examples where artists have looked at shape-change to create mostly visual artworks. However, artists have also explored the possibilities offered by purely tactile media. One interesting case is "Mobile Feelings" (2002-2003) developed by Christa Sommerer and Laurent Mignonneau [135]. Through this work, the artists tried to reimagine the aesthetics of mobile communication 7.3. Instead of looking at phones as devices for making voice calls or sending text messages, they explore the delivery of feelings. By using an organic-shaped device, two people can share their heart-beat and blood pressure among distance, by creating a very intimate type of communication.

We showed that by using malleable media, this type of experience can be enhanced through shape-change. In the case of "Vital+Morph" bio-physical signals are presented through a change of devices geometry. This type of deformation can lead not only to haptic experience but involving other senses. As we already discussed, the motion produced by shape-change leave to users a sense of aliveness of the de-

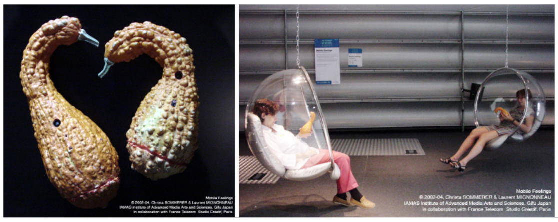

Fig. 7.3. “Mobile Feelings“: the devices (left) and the installation (right).

vice and a strong presence of data that it displays. Moreover, with “Volflex++” we showed how digital data could be more specifically encoded into materials properties like rigidity.

7.2.3 New Materials for Media Artworks

One element that connects media artists to previous forms of art, is the research of new materials 7.4. In order to make digital data and processes physical, media artists have started to explore the possibilities offered by the so-called smart materials, which means materials that can have one or more characteristics that can be controlled through external stimuli. One of the most notable examples is the work done by Sachiko Kodama with ferrofluid. Since her first installation “Protrude, Flow” [136], she has explored the aesthetical possibilities of ferrofluid for creating emerging and shape-changing sculptures that react to digital processes such as sound. Similarly, Wakita et al. [137] have worked on the creation of a magneto-rheological material called “pBlob”. This deformable material can be controlled through computer controlled magnetic coils to create physical shapes that behave like blob-like computer graphics simulations. In his installation “Biomatrix”[4], sculptor Kohei Nawa proposed a concept of a display made of a hybrid digital-physical material named “PixCell”. which appears like a biological membrane that deforms and flows like a living organism.

[4] `https://www.scaithebathhouse.com/en/exhibitions/2018/09/biomatrix/`

Fig. 7.4. Three interactive materials for media art: “Protrude, Flow” (left), “pBlob” (center), “PixCell” (right).

The use of liquid smart materials can result in beautiful and stunning visual experiences. However, materials like ferrofluid or other compounds, cannot be experienced fully, since they cannot be touched for safety reasons. Moreover, such materials react to external such as the one of an electromagnetic field. Such type of actuation usually requires elements such as coils and power requirements that make difficult to miniaturize and make transportable. Our project “Vital+Morph” shows how by devising the proper metaphor we imitate the behavior of such liquid materials, but at the same time they can be controlled precisely, and users can explore the material with their hands, and even grab it. To allow this type of interaction, embedded actuators must be used in combination with deformable materials. Obviously, it is not possible to obtain the same type of transformations and programmability. However, the focus of Malleable Media is on haptic communication. Therefore every choice (both technical and conceptual) has to be oriented towards this aspect. Through “Volflex++” we showed how computational controlled balloons could support a change in viscosity, that is not only visually perceivable but mostly perceivable through the sense of touch.

Through the projects presented in this thesis, we have outlined the concept of Malleable media. Such types of new media can push media arts towards a new stage by providing a new set of shape-changing materials, as a new class of hybrid materials that combine deformable compound structures and embedded sensors and actuators.

Such types of media can provide the base to create dynamic and engaging physical representations of digital data that can be experienced through the tactile sense.

7.3 Applications

Malleable media such as Volflex++ and Vital+Morph can be further used for different purposes. We outline three main application scenarios. These can be explored by future research, that will serve to test them and foster the understanding of this type of media.

7.3.1 Generation of Physical-Virtual Forms

As we showed throughout this thesis, an essential element of malleable media is their 'organic' appearance. This organic looking derives both from the use of compliant materials and from the use of bio-inspired metaphors. We showed in Chapter 4, architects have made extensive use of bio-inspired metaphors. This has generated specific tendencies in contemporary architecture. One of them is known as *blob architecture*. Architect Greg Lynn proposed this term to denote organic and globular architectural forms [138]. Aesthetically, such architectures are characterized by soft and sinuous shapes. Blob architecture is a product of virtual simulation of shapes, through the use of computer graphics techniques such as "metaballs". We believe that a system like Volflex++ can be used to provide a physical counterpart of the computer graphics simulation. This can give the possibility to architects to render such blob-structures not only on a screen but also physically. Differently, from 3d printed prototypes -which are widely used in architectural firms- malleable media can change their size together with a virtual simulation. Moreover, architects can benefit from the possibility of rendering physically different types of rigidities. Since some of the major concerns of architects are related to the structural qualities of a building, a system like Volflex++ can help them to test the reaction of a structure -or at least to its surface- to different types of stresses applied onto it. This may give to architects interested in developing blob-like building a way to experience and test their virtual models in a physical manner (Figure 7.5).

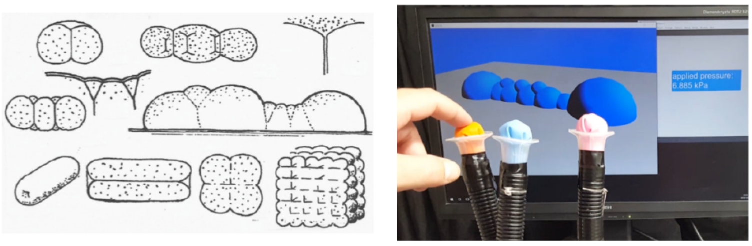

Fig. 7.5. The use of malleable media for form finding. On the left, a series of illustrations by Frei Otto on the use of pneumatic structures for architectural structures. On the right, Volflex++ for structural modeling of blob-like architecture.

Similarly, malleable media can be used to present physically other types of organic content that today is possible to experience only through a visual display. For instances, it can be possible to represent human organs, based on images from fMRI or reconstructions from 3D scanning. This may be useful for training doctors or medical personnel to develop skills related to palpation. As we showed in Chapter 6, a system like Volflex++ can present several types of rigidities that can be correctly discriminated by humans' fingers. On the other hand, it can be used to enhance the experience of a woman during her pregnancy. We found that shape-change can be effectively used to communicate the sensation of the aliveness of something distant. In this case, an ultrasonic video image of a fetus in the womb can be presented physically, and a person might be able to touch them, feeling the softness and see the physical growth 7.6.

7.3.2 Physical-Virtual Musical Instruments

Another possible application of malleable media is in the creation of new musical instruments that are both virtual and physical. Nowadays there is a clear separation between acoustic instruments and digital controllers, used to play virtual synthesizers.

Fig. 7.6. The use of malleable media for the simulation of organic shapes. On the right, interacting three-dimensional data of a fetus in a womb.

For instances, drums are available in different sizes, and materials. The rigidity of the surface, its material, and the size determines the sound of a drum. However, commercially available controllers are just a flat rigid surface. Through malleable media, we can think of combining the physical characteristics and the haptic feedback produced by the interaction with an acoustic instrument, and the flexibility offered by virtual synthesis. A drummer can decide to play a digital drum with a high pitch but high resonance. In this case, the surface will become large and rigid. Then, if the sound will be changed to a low pitch one, the surface will become softer (Figure 7.7). As already noted by several researchers [139, 140], the most important element for providing haptic feedback in virtual musical instruments is the presence of direct contact with a physical surface.

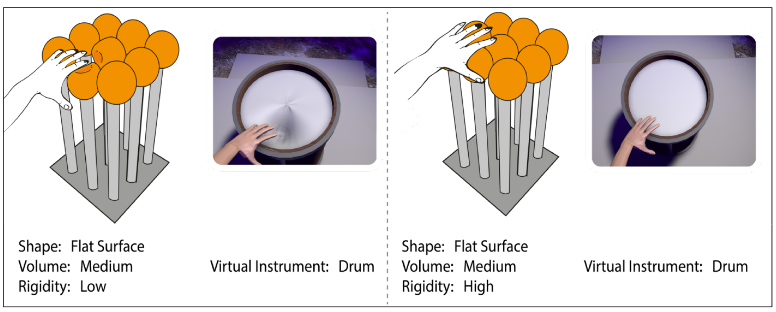

Fig. 7.7. An exampled of a physical-virtual drum using malleable media.

7.3.3 Circle Packing Displays

As shown in the previous chapters, most of the system that uses shape-change for presenting data reference to bar graph. Such graphs are useful when we need to compare discrete categories. However, this is not the only way to represent data graphically, and therefore physically. For instances, *circle packing* is a popular variation of a Treemap graph used in data visualization [141]. Circle Packing uses circles instead of rectangles, and each circle contains different circles to represent a certain level of hierarchy. The area of each circle can also be used to represent other types of data, such as quantity or size. Circle packing representations are used when there is the need to represent hierarchical relations and compare proportions. We think that both Vital+Morph and Volflex++ can be used as a physical counterpart of Circle Packing visualization (Figure 7.8). Moreover, such systems can also offer additional mapping possibilities between data and their physical representation. If in a visual rendering, colors and sizes are used, with a malleable media, time can be used. The physical surface can change geometry or size to represent a variation of a certain type of values in real-time. Additionally, rigidity and haptic feedback can be used to communicate other types of values to a user. In this case, a combination between the characteristics of Volflex++ and the portability of Vital+Morph can generate a new type of display for real-time presentation of data who benefits from the use of a Circle Packing metaphor.

7.4 From Haptic Interfaces to Shape-changing Materials

The main difference between the work presented in this thesis and previous works in the field of haptics and HCI lies in the concept of interface. Especially from the perspective of HCI, the world humans inhabit is considered as mediated by tools. In this context, haptic interfaces are instruments used to support the execution of a specific task. However, works such as “Vital+Morph” and “Volflex++” dont have an

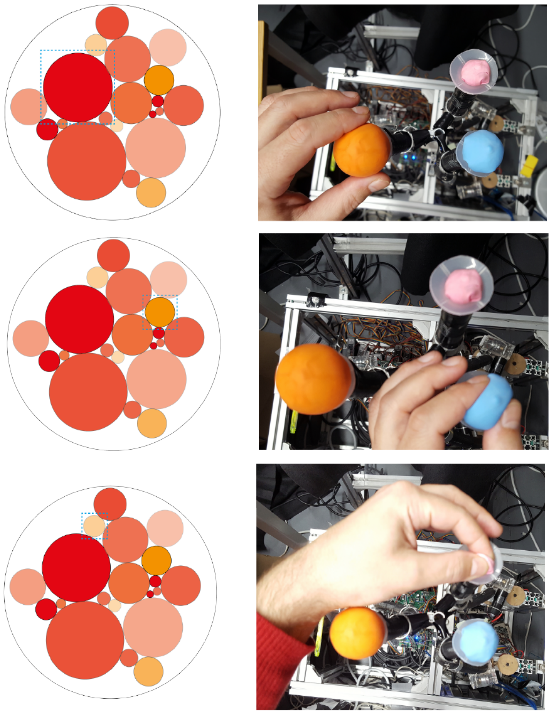

Fig. 7.8. The use of malleable media for the creation of a circle packing displays for data physicalization.

instrumental purpose but are designed to support haptic communications and create feelings that must be perceivable by users through their hands.

This brings us to a fundamental difference between direct touch and tool-mediated touch. First, the use of tools introduces different levels of spatial and perceptual transformations that users brain has to invert [94]. From this point of view, force-feedback devices are much more easy to implement compared to other types of haptic interfaces, since the brain of the user already assumes the existence of a tool. Second, since mediation is the primary focus, researchers have developed an equivalence between "interfaces" and "tools", leading to what Cadoz et al. have defined as instrumental interactions [139]. As noted by Gillespie and OModhrain [10] the notion of "interface" becomes irrelevant if we consider computational artifact having the same role and characteristics of the other artifacts and objects that occupy our physical world.

Moreover, they noticed that by removing the word interface can be liberating, especially when the focus of the device is on haptic perception. This can free designers from the preoccupation of supporting or facilitating a task, and concentrate on the tactile experience, and shift the focus on the feel they want to create for a user. We, humans, are embodied creatures that explore the environment and learn from it by experiencing it with our bodies. Leaving behind tools and mediations we also shift the emphasis from supporting "un-skilled" with the design of with new tools (as done in general HCI), we shift towards the design of objects and materials that display, embody, and respond to digital information. In this case, skills become an essential component of the haptic experience and are a necessary component since they represent the way how we build our knowledge of the world [10]. This may be reinforced by the considerations of Ishii et al. [38], which calls for the establishment of a new discipline that can be defined as Human-Material Interaction (HMI), that can embrace this new perspective of design and interacting with computational objects. We propose to define such systems as Malleable Media. The works presented in this thesis may not be applicable for utilitarian purposes. However, but the mere curiosity to experience a new perspective is enough for people to engage with malleable media. Going back to the definition of McLuhan, if the "*medium is the message*", what is the message of Malleable Media? We can say that apart from the specific content displayed- the message of Malleable Media is their materiality, being highly tactile objects composed of materials that change their physical properties to communicate and represent digital information to humans, and can require and high level of physical engagement.

8. CONCLUSION

This dissertation introduced the concept of malleable media and its implications in the design of new types of shape-changing materials to connect the physical reality and virtual realities. This framework was defined through the design and evaluations of two systems, Vital+Morph and Volflex++. Such projects have been developed using an interdisciplinary approach that crosses engineering, HCI, haptic perception, design, and art. In the thesis, we described the design process, the technical implementations, and their evaluations. We provided a psychophysical experiment and a user study in the context of a media art installation. Also, we proposed a discussion on the characteristics that need to be considered in the design of malleable media and future applications in media arts.

We place our main contribution in emerging tendency in media arts of researching and designing new hybrid materials that can represent digital contents physically. However, by physical qualities, we mean as physically perceived through touch. This marks a difference since most of the previous works concentrate on visual perception. Moreover, we provided several specific applications, such as data physicalization and synchronization between physical and virtual objects.

We conclude by summarizing how the work presented in this thesis answers to the main research questions stated in the Introduction 8.1.

- *How to realize Malleable Media?* The creation of shape-changing materials represents an open question in research. Very few technologies have been explored, and all of them depends on the specific type of shape-change a designer wants to enable. In this thesis, we proposed two main ways to realize shape-change. Through Vital+Morph we explored two mechanisms for realizing the change of geometry. As for the Vitals, we proposed a mechanism that can deform a paper cylinder. In contrast with previous works, we proposed a system that is both light, self-powered, and enabled for IoT. In addition, the material is soft and can be held in users hands, while previous works focused on rigid materials. As for the Morph, we proposed a mechanism that can enable not only a change of geometry of a circular shape but this change can be transmitted to a paired device through the internet. The transmission of shape-change is still an underexplored area in research. Through Volflex++ we proposed the Volflex technology as a possible candidate for implementing complex and versatile shape-changing materials. In this case, we concentrate on the change of size and rigidity. While previous works focused on the change of size only on a vertical dimension, we propose the change of size for volumetric surfaces. Regarding the change of rigidity, we propose a mechanism that can present surfaces that can range from soft to stiff. Previous research looked at mechanisms that can produce a surface to became or soft or stiff but cannot offer a transition between these two extremes, and therefore they miss all the rigidities that are in the middle of soft and stiff. Previous systems allow change of size and rigidity as separate. Through Volflex++ it is possible to achieve such changes on a single surface and simultaneously. Most importantly, we propose mechanisms for shape-change oriented to haptic perception. As we showed in the previous chapter, the change of shape is often used to address the visual sense, and many of the systems presented cannot be touched by users. Both Vital+Morph and Volflex++ can be grabbed and directly manipulated by a users hands. They also produce noticeable haptic feedback and can support both active and passive touch. We believe that the tactile sense should be the first channel of communication of shape-changing materials.

- *How Malleable Media are perceived?* As noted by many researchers, the perception of shape-change is still not very well understood. In this thesis, we focused on two aspects of perception that have not been covered by previous work. The first is the haptic perception of shape-change. Through Vi-

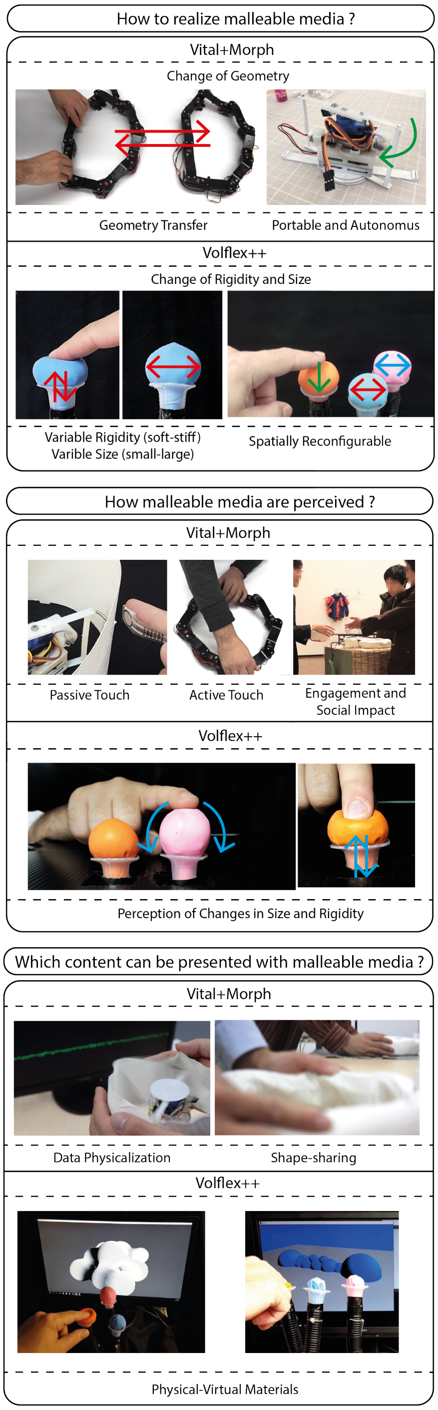

Fig. 8.1. A summary of the main contributions of this thesis.

tal+Morph we showed how the proposed mechanism can not only represent digital data through the change of geometry which can also be perceived visually- but that the movements caused by shape-change can produce force-feedback. This adds a new dimension to data physicalization, which was not explored before. Through Volflex++ we performed a user study using psychophysical methods. We wanted to elucidate the haptic perception of the change of size and rigidity. Such kind of studies has not been performed yet for the evaluation of shape-changing materials. Since Volflex++ can represent a large variety of sizes and rigidities is fundamental to understand which is the perceived resolution of the user. Moreover, we found that the cues offered by this system are consistent with the perception of real materials with similar sizes and rigidities. Through this study, we aimed to bridge the methodologies and work done in haptics research for the study of shape-change. The second aspect we wanted to elucidate is the broader perception of malleable media, and try to anticipate which this type of impact these media will have on society. Being a new type of media, it is not really clear how shape-change will be perceived in everyday life, and how possible users interpret this type of communication. In contrast to previous work, we propose to evaluate new technologies through a media art installation. This type of evaluation gave us the possibility to collect a wide range of opinions, that confirmed our design but also warned us for possible misunderstandings and issues that such type of media can present in society. Differently, from previous work, we looked at the perception of shape-change through different perspectives. This helped us to provide additional knowledge that was absent in previous studies, which focused on the evaluation of specific tasks or visual perception only.

- *Which content Malleable Media can present and how?* Content design and utilization is another open issue in research. It is not clear which content can be presented with shape-change, and for which application applications such media are useful. Through Vital+Morph we proposed data physicalization, which seems to be a suitable application area for shape-change. However, we propose a very specific application domain, such as the communication between a patient and his/her family over distance. Most of the previous works focused only on data, we considered where and how these data are generated, and in which context shape-change is used. We also investigated biomedical data, such as Vital Signs, while previous works looked at very general datasets and never looked at very specific data and their implications. We showed that data sculptures (which are very specific, while researchers on dynamic physicalization tended to create very general representation media, which are not dependent on the dataset displayed. Through our research, we propose to bridge these two aspects, and highlighting that the design choice and aesthetics chosen by the designer can enrich the communication and representation of data. Moreover, we showed that in order to be effective, data has to be interpreted artistically by a designer through the choice of metaphors that has to be consistent with the data displayed. Through Volflex++ we outlined several scenarios where shape-change can be used. We proposed to look not only at data physicalization, but also at virtual musical instruments and digital architecture. Especially, we developed a method that can present virtual objects in their full components, by synchronizing different types of visual, haptic, and auditory feedback. In the context of the research on shape-change, sound is often omitted. We proposed a method that can interactively represent the sound generated by virtual objects through direct contact with the shape-changing surface. Through our system, the sound model can change dynamically and follow the characteristics of the material presented by the surface. Moreover, both Vital+Morph and Volflex++ suggest how Malleable Media are suitable for presenting both data and virtual objects which are 'organic'. This can open a new way of creating media artworks, such as shape-changing sculptures and installation that can be directly touched and experienced physically by users.

Such systems have been presented both in the form of publications and public presentations, in international conferences, scientific journals, and media arts festivals. They have been validated by the general public and subjects for experiments. While the design and implementations of Vital+Morph and Volflex++ can be seen as engineering contributions, these systems are viewed under the lens of malleable media. The concept of malleable media, and the examples provided in this thesis, point towards a near-future where humans will be exposed to a reality where virtual and physical are mixed, thanks to shape-changing materials. Beyond the idea of 'user interface', such materials will not be used to mediate our actions with computational processes but will allow us to experience digital information through our body, as we do now with objects and material that composed our environment.

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