Designing Serpentine-Shaped Robotic Appendages for Augmenting Daily Interactions

日常環境のインタラクションを拡張する取付式蛇型ロボットの設計

February 2020

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Abstract

Augmenting humans with robotic appendages have long been envisioned in sci-fi and pop-media. Recent advances in robotics have also demonstrated prototypes that could satisfy such vision. However, existing research literatures have several limitations. First, most works are very focused on specific domains, such as industrial applications or rehabilitation. While these tasks are useful, daily usage constitutes many other use cases that are more relevant to everyday life. Secondly, knowledge from wearable systems and human-computer interactions research indicate that daily worn devices constitutes additional set of design requirements and challenges, such as wearability and ergonomics, social and user acceptability and user experience design. These challenges were not addressed in any surveyed related literatures.

To achieve the intended contributions, this dissertation focuses on the serpentine morphology (snake-like) as a wearable form factor to realize this form of wearables. The serpentine morphology was chosen as it has established flexibility and versatility in various application domains. Accordingly, its versatility is also demonstrated through the four case studies that were developed and evaluated, further demonstrating its potential as robust wearable form factor. This dissertation is the first to examine wearable serpentine-shaped robotic appendages for everyday use.

This dissertation addresses the mentioned research challenges by conducting nine evaluations, developing four case studies, and analyzing the results of these processes in order to make four main contributions. The first contribution tackles the problem of understanding the contextual factors in the usage domains, design requirements and expectations of daily worn serpentine-shaped robotic appendages. The conducted work addresses the fact that the usage domain, requirements and expectations of this form of wearable systems are not formally investigated or identified in surveyed works. This contribution is addressed by conducting two evaluations that addressed daily usability expectations, where the resulting use cases are analyzed, structured and classified. The resulting use case distributions enable identifying various domains of daily interaction expectations. This contribution is significant; it is the first to provide insights about the interaction expectations, which in turn forms a broad understanding of the main usage expectations and potential challenges of serpentine-shaped robotic appendages. The provided data, analysis and insights contributes with a comprehensive resource from which design considerations, implementation methods and evaluation criterion can be derived.

The second contribution focuses on identifying factors affecting acceptability on a personal and a societal scale. Previous works within wearable systems provide a number of insights to address various acceptability requirements, yet identified factors are applicable to standard wearable systems. Serpentine-shaped robotic appendages present new challenges for public and personal acceptability that have not been previously identified. Accordingly, this dissertation contributes with new knowledge about the main factors affecting personal and social acceptability, which are extracted through a series of case studies and evaluations results. The significance of this contribution lies in the presented insights and methodologies on which social and personal acceptance are addressed, where these insights contributes to addressing social challenges as well as ensuring user adoption. Previous efforts within the area have focus on functional efficiency and technical novelty, therefore, there is a dearth of works that tackled essential social and personal acceptability challenges that would equally affect a wearable's daily use.

The third contribution addresses a critical problem; how can we design user interaction experiences for serpentine-shaped robotic appendages? The multipurpose nature

of these robots' present challenges that were not addressed in single purpose wearable systems. Therefore, insights are extracted from the design, development and evaluations of the case studies, where they are structured and presented. These insights provide valuable considerations and methodologies for developing multipurpose user experiences that target daily use. Previous research efforts in multipurpose wearable systems have presented various interaction possibilities, yet these works do not address the mean of enabling multipurpose user experiences. Therefore, this contribution constitutes design insights about the design methodology of cohesive multipurpose user experiences, as well as a classification and embodiment of novel digital experiences that were not previously investigated in related research literatures.

The fourth contribution comprise an effort to structure gathered insights from the design, implementation and evaluation procedures of the case studies, by providing a multi-dimensional set of essential user-centered design considerations for constructing serpentine-shaped robotic appendages. The design dimensions include four main sub-domains, which are multipurpose use, interaction design, wearability and ergonomics, and unobtrusiveness and social acceptability. These design considerations provide both design guidelines and implementation methods based on the culmination extracted insights from case studies and their evaluations.

We conclude with a discussion of limitations and future work directions, emphasizing the means to advance this domain by focusing on various interleaved factors, such as technical, interaction, or social oriented research challenges and opportunities.

Table of Contents

Table of Figures

List of Tables

Chapter 1   Introduction

1.1   Motivation

Human augmentation has always been embraced in science fiction literatures and multimedia as a mean to advance human innate abilities. Authors of such literatures have often envisioned humans with extended natural senses abilities, such as effortlessly lifting heavy objects or equipping our eyes with night or heat vision capabilities. Such visions constitutes seamless fusion of humans and technology into one being, often called a cybernetic organism (Cyborg) (Manfred E. Clynes and Kline 1960). An interesting aspect of the Cyborg vision is the coherent integration of mechanical components into our bodies, amplifying our physical interaction abilities.

There exists numerous examples from pop-culture, notable ones are from spider-man's Dr. Octopus (Marvel 2019) and Metal Gear's Screaming Mantis (Konami 2019). These works envision wearable robots, often integrated with the nervous systems of the wearer, which can be controlled and used as innate limbs, thereby amplifying wearer's interaction abilities. Various artistic works, such as the Stelarc project (Stelarc-Project 1980), explored how a human with multiple limbs can carry-out work within an artistic setting.

From a research perspective, recent research literatures explored wearable robots that fulfil and extend the cyborg vision. Various intriguing works, such as Asada et al's (Wu and Asada 2014), investigated using extra robotic arm and fingers for carrying out various physical object manipulations. While these visions are technically novel, convincing a casual user to wear and use such robots on a daily basis constitutes a multitude of interconnected challenges that span beyond what have been investigated.

Accumulated knowledge from HCI have shown that users have a complex relation to technology (Gemperle, Kasabach et al. 1998, Dunne and Smyth 2007, Lazar, Koehler et al. 2015, Liu, Vega et al. 2016), thereby affecting their adoption and usage within daily contexts. For example, wearable computers (Starner 2001) have been extensively studied for more than 30 years throughout HCI communities, where numerous prototypes were proposed and evaluated. While existing works about wearable robotic appendages are technically novel, these forms cannot be adopted within our daily lives. For example, although some form of

wearables like smartwatches became common in the last 5 years, other forms of wearable systems, such as head mounted displays or wearable haptic feedback systems (Ion, Wang et al. 2015, Dementyev, Kao et al. 2016, Je, Choi et al. 2017), are yet to be commonly worn and used in daily contexts. We believe that envisioning daily usage of multipurpose robotic appendages constitutes the same challenges that hindered earlier wearable computers. Therefore, it is viable to extend and build upon the well-established knowledge within HCI to similarly study and investigate how robotic appendages can be used in day to day contexts and for the casual user.

From an HCI standpoint, existing research literatures about wearable robotic appendages have several limitations. The works are very focused on specific domains and difficult to generalize. For example, the majority of works focuses on industrial applications, such as drilling or lifting heavy machinery (Llorens-Bonilla, Parietti et al. 2012, Bonilla and Asada 2014, Parietti and Asada 2016). While industrial contexts and tasks are useful, daily usage constitutes contexts and tasks far beyond the ones presented and evaluated. Significant results regarding the expectations of daily worn appendages, presented in this dissertation, indicate that users expect such wearables to fulfil a variety of daily tasks far beyond what have been suggested in existing research literatures. Moreover, existing research literatures solely focus on physical manipulation of surrounding objects, where their prototypes were mechanically optimized for mentioned tasks. While such design direction is advantageous for industrial and work related contexts, designing wearable systems for daily use constitutes additional set of criterion that are equally essential, including multipurpose use (Starner 2001, Clawson, Pater et al. 2015, Koelle, Ali et al. 2017). Lastly, developing a wearable for daily use constitutes challenges within ergonomics, wearability, social and user acceptability and interaction design, which were not addressed within any existing literatures. In order to address the challenges of realizing wearable robotic appendages, novel wearable designs, implementations and evaluations should be conducted, taking into consideration mentioned interconnected factors to realize multipurpose daily worn robotic appendages.

Based on the before mentioned shortcomings of existing works, the motivation of this dissertation is to takes the first step to envision, explore and evaluate multipurpose robotic appendages for use as daily augmentation wearables across different everyday contexts. This dissertation bridges the gap between HCI and wearable robotic appendages by contributing with a series of studies and extracted design insights and considerations for designing and evaluating such emerging wearable systems. In contrast to existing works that focused on other anthropomorphic robotic arms (human-like), this dissertation focuses and extends the snake form factor (serpentine) for use as wearable robotic appendage, which has proven versatility within robotics research. We envision a class of robotic wearables, which we called Serpentine-Shaped Robotic Appendages, which are able to fulfil a variety of tasks while being comfortably and unobtrusively worn throughout the day.

This research adopts a user-design approach, which is a well-established approach for designing and evaluating systems with interconnected requirements and ambiguous usability contexts (Lazar 2007). Accordingly, our research is structured in three main phases. First, we conducted two studies that investigated the user requirements and expectations of serpentine-shaped robotic appendages, and explored research challenges and opportunities from robotics and HCI perspectives. Second, four prototypes where developed, where their implementation specifics and interaction potentials are discussed. A series of seven evaluations are carried out using the developed prototypes. Third, insights are elicited from the evaluation results, where they are combined and analyzed to extract design insights and considerations. The feasibility of realizing the design considerations is also discussed, where survey of context-awareness, actuation methods, and mechanical design have shown that implementing serpentine-shaped robotic appendages for daily life is feasible in a limited

implementation scope. Therefore, we believe that the outcomes of this dissertation will both encourage and enable researchers to realize novel serpentine-shaped robotic appendages based on presented design insights and considerations. Moreover, we believe this dissertation provides a foundation covering design, implementation and evaluation approaches that can form the basis to establish this class of wearable systems for daily use.

1.2   Main Research Questions

There exist numerous challenges in designing, implementing and evaluating a daily worn robotic appendage. This dissertation focuses on a sub-set of these problems, which are presented in the following research questions (RQ):

1- What are the user interaction expectations and tasks associated with daily worn serpentine-shaped robotic appendages?

2- What are the main social and user acceptability challenges? And how can we address these challenges?

3- How can we design cohesive and cross-contextual user experiences for this form of multipurpose wearable devices?

4- From the perspective of multipurpose use, social acceptance during public use, and cross-contextual user experiences, what are the main design considerations required for realizing serpentine-shaped robotic appendages?

Previous works have examined a subset of above questions within the research domains of wearable computing and supernumerary robotic limbs. For example, actuated and fashion wearables examined various interaction possibilities, yet they remain limited in their evaluation scope and validity of interactions across different contexts. In contrary, this work is the first to utilize an iterative bottom-up user-centered design process to elicit, embody and evaluate serpentine-shaped robotic appendages. Such research method allows establishing design objectives and evaluations based on concrete user-elicited knowledge. Moreover, this work is the first in structuring and presenting a set of design considerations that address multiple serpentine-shaped robotic appendages design challenges, namely in designating the multipurpose usage domains, wearability and ergonomics, user-experience design and public use. These design considerations and requirements have not been fulfilled in previous works. Therefore, addressing the research questions contribute with forming a user-centered understanding of how a serpentine-shaped appendage may be design for daily use, as well as identify and establish fundamental design considerations that future systems should fulfill.

In order to address RQ1, a series of studies was carried out to investigate the requirements and expectations of daily used serpentine-shaped robotic appendages. Through these evaluations, the results were analyzed and classified to form a comprehensive use case distribution and a classification, which reflect daily usage expectations. The case study distributions bridge the knowledge gap in identifying and classifying main usage expectations by providing designers and practitioners with a user-elicited list, analysis and a classification. Such information can be used as basis to derive design objectives that future wearable systems can be designed to achieve, or to establish evaluation criteria by which future wearable systems can be evaluated against. The specifics of this analysis and its extracted insights and results are discussed in section 5.1.

Although social and user acceptability is thoroughly discussed within wearable computing research literatures, there is a dearth of studies that tackled public wearability and usability of wearable robots. Therefore, addressing RQ2 enables identifying and fulfilling the

factors effecting social and user acceptability of serpentine-shaped robotic appendages, which to the best of our knowledge, have not been previously identified or addressed in previous works. The implication of addressing this research questions also provides significant generalizable insights towards developing wearable robots that target daily usage contexts. RQ2 is addressed in section 5.2

Designing an interaction experience that enabled multipurpose use is also a research challenge that have briefly been addressed in previous works. While there exists a number of research literatures that presented multipurpose wearables (section 2.5), these works mainly emphasized technical novelty and explored interaction potentials. However, the mean of achieving a cohesive multipurpose interaction experience is not explored. Therefore, addressing RQ3 enables us to address the factors required for constructing cohesive experiences that enabled multipurpose use as wells provides the efficiency needed in each task domain. RQ3 is specifically addressed in section 5.3.

The culmination of the insights extracted from addressing the research questions will enable forming an overall understanding of the main design factors effecting daily use. Therefore, these factors are combined, analyzed and presented as design considerations to address RQ4. As these factors are embodied within the case studies, future wearable daily worn robots can be built to embody a similar design direction as the case studies, or to realize these factors in different methods. Accordingly, each design consideration is discussed, and a methodology to implement each design consideration is presented based on design and development of the case studies. The design considerations are discussed in Chapter 6.
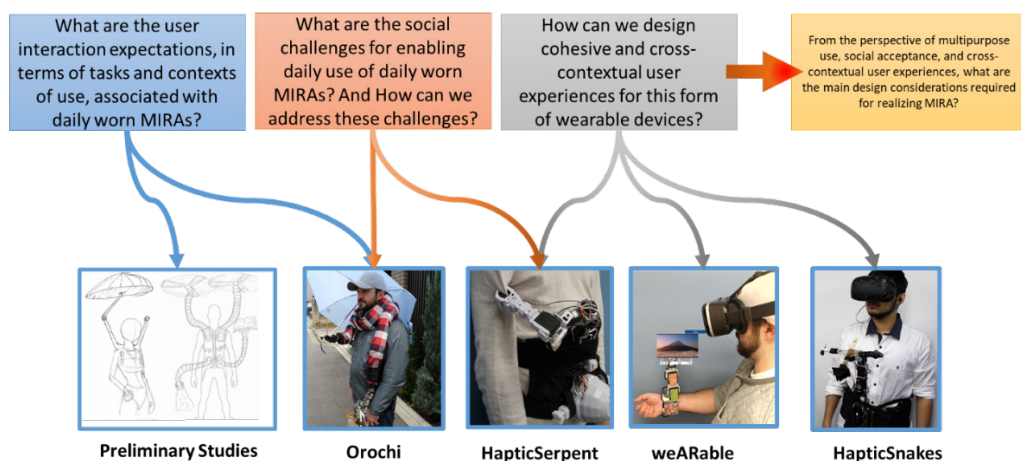
Figure 1 this figure illustrates which case study/user study addresses which research question.

1.3 Projected Contributions and Research Emphasis

1.3.1 Projected Contributions

By Addressing the before mentioned research questions, this thesis has the following projected contributions:

1. Identification, analysis and classification of daily usage expectations and domains of serpentine-shaped robotic appendages within everyday contexts.

2. Identification of social and user acceptability challenges, and the methods to address and accommodate these challenges and requirements.

3. Design and Implementation of novel user experiences that demonstrate:

- How cohesive user experience can be designed to enable multipurpose use.

- Identification and classification of novel cross-device user experiences enabled by serpentine-shaped robotic appendages.

4. Identify and discuss essential design considerations to enable researchers and practitioners to design and evaluate serpentine-shaped robotic appendages against user requirements and expectations.

These contributions are essential for advancing research about snake-shaped serpentine-shaped robotic appendages. The *first contribution* tackles the problem of understanding the contextual factors in the usage domains, design requirements and expectations of daily worn serpentine-shaped robotic appendages. The conducted work addresses the fact that the usage domain, requirements and expectations of a physical augmentation wearable are not formally investigated or identified in surveyed works. This contribution is addressed in section 5.1 , which provides an analysis and structuring of use case distributions and classification that enable us to identify various domains of daily interaction expectations. This contribution is significant; it is the first to provide insights about the interaction expectations, which in turn forms a broad understanding of the main usage expectations and potential challenges of serpentine-shaped robotic appendages. The provided data, analysis and insights contributes with a comprehensive resource from which design considerations, implementation methods and evaluation criterion can be derived.

The *second contribution* focuses on identifying factors affecting acceptability on a user and a societal scale. Previous works within wearable systems provide a number of insights to address various acceptability requirements, yet identified factors are applicable to standard wearable systems. Serpentine-shaped robotic appendages present new challenges for public and user acceptability that have not been previously identified. Accordingly, this dissertation contributes with new knowledge about the main factors affecting user and social acceptability, which is extracted through a series of case studies and evaluations results. These insights are discussed in section 5.2 Social and User Acceptance. The extracted insights about this domain advances the state-of-the-art robotic systems by identifying factors that contribute to wider acceptability, and thereby user adoption. The significance of this contribution lies in the presented insights and methodologies on which social and user acceptance are addressed. Previous efforts within the area of robotic appendages have focus on functional efficiency and technical novelty (e.g. (Bonilla and Asada 2014, Wu and Asada 2014, Leigh and Maes 2016), therefore, there is a dearth of works that tackled essential social and user acceptability challenges that would equally effect a wearable's daily use (Shinohara and Wobbrock 2011, Dobbelstein, Hock et al. 2015, Profita 2016, Schwind, Deierlein et al. 2019).

The *third contribution* addresses a critical problem; *how can we design user interaction experiences for serpentine-shaped robotic appendages?* The multipurpose nature of these robots present challenges that were not addressed in single purpose wearable systems. Therefore, insights are extracted from the design, development and evaluations of the case studies, where they are structured and presented in section 5.3. Previous research efforts in multipurpose wearable systems (Dementyev, Kao et al. 2016, Leigh and Maes 2016, Leigh, Denton et al. 2018) have presented various interaction possibilities, yet these works do not address the mean of enabling multipurpose user experiences. Therefore, this contribution constitutes design insights about the design methodology of cohesive multipurpose user experiences, as well as a classification and embodiment of novel user experiences that were not previously investigated in related research literatures.

The *fourth contribution* comprise an effort to structure gathered insights from the design, implementation and evaluation procedures of the case studies, by providing a multi-

dimensional set of essential user-centered design considerations for constructing serpentine-shaped robotic appendages. The design dimensions comprise three main sub-domains, which are multipurpose use, interaction design, wearability and ergonomics, and unobtrusiveness and social acceptability. These design considerations provide both design guidelines and implementation methods based on the culmination extracted insights from case studies and their evaluations. The design considerations are discussed in Chapter 6.

1.3.2   Research Emphasis and Assumptions

This thesis focuses on a set of aspects when designing and evaluating the presented works. These aspects are the emphasis on 1) Daily Use *2) wearability, 3) the Serpentine Morphology 4) user-centered research approach*. These aspects are presented and discussed within the next subsections as follows:

1.3.2.1   Daily Use

Compared to previous research on wearable appendages (e.g. (Llorens-Bonilla, Parietti et al. 2012, Wu and Asada 2014, Parietti, Chan et al. 2015)) that emphasized industrial and work related tasks (e.g. drilling, holding heavy equipment or maintain user's balance), this dissertation focuses on daily use. The challenges and usage expectations surrounding daily use are different than those within industrial or work related contexts (Sears, Lin et al. 2003, Tamminen, Oulasvirta et al. 2004, Barnard, Yi et al. 2006), accordingly, wearables designed for such context must adhere to different requirements (Dobbelstein, Hock et al. 2015, Profita, Farrow et al. 2015, Profita 2016). Therefore, daily use is emphasized as a main assumption and target context throughout the case studies, evaluations and analysis.

1.3.2.2   Wearability

Wearability is defined as the active relationship between the wearable's physical shape and the wearer's body. Gemperle et al. (Gemperle, Kasabach et al. 1998) Although this concept may encompass numerous aspects, we focus on the fundamental fact that the device is expected to be attached to the user's body in almost all their daily contexts of use. Therefore, this dissertation assumes that serpentine-shaped robotic appendages would mainly be utilized as wearables, where they can be used to enhance the user's day-to-day interactions physically and digitally. To achieve mentioned objective, we focus on the utilizing the flexibility enabled by the serpentine form factor to address interaction and wearability challenges associated with daily use. Accordingly, some use cases involve taken-off serpentine-shaped robotic appendages are presented and discussed to illustrate the flexibility and potential of using such wearables in different contexts of use. However, usability while worn is the main focus of this dissertation.

1.3.2.3   Serpentine Morphology

This dissertation focuses on the serpentine robot morphology (snake-morphology). Snake robots have long been investigated within robotics communities (Hirose and Morishima 1990). The flexible structures of snake robots allows them to be versatile across a wide range of tasks, such as search and rescue (Erkmen, Erkmen et al. 2002), inspection (Granosik 2005), or manipulating objects (Hirose and Umetani 1978). Therefore, utilizing serpentine shaped robots provide numerous interaction potentials. However, such morphology is minimally investigated within HCI, and especially in wearables.

Although Serpentine-shaped robotic appendages and standard serpentine robots share the same morphology, they have different application domains, and thereby different design considerations and research challenges. For example, serpentine-shaped robotic appendages are designed as multipurpose, therefore, they are expected to carry out varied

physical and digital interactions while being worn. Wearability also impose a number of limitations in terms of design, for example, they have to be light weight and comfortable to wear. Lastly, safety is a major challenge for serpentine-shape serpentine-shaped robotic appendages, as their close proximity to the users' body pose a constant source of danger. The mentioned requirements and challenges are not necessarily essential for traditional serpentine robots that carry out explorative or inspection tasks.

1.3.2.4   Iterative User-Centered design and evaluation research approach

User-centered-design (UCD) is an iterative design and evaluation approach broadly used for designing systems, products and services (Norman and Draper 1986, Smailagic and Siewiorek 1999, Earthy, Jones et al. 2012, Oh, Kim et al. 2013). As UCD enable a variety of advantages for rapid prototyping, evaluation and knowledge extraction, UCD is adopted as the main research approach of this dissertation. Employing UCD enable rapid development and evaluation of various specific requirements and criterion without emphasizing complete prototypes. Therefore, in addition to carrying out various evaluations based on the UCD (e.g. focus groups, surveys…etc), the developed prototypes reflect specific design and evaluation requirements, and therefore, do not reflect all design or implementation requirements. However, since realizing serpentine-shaped robotic appendages is essential for generating future case studies based on this dissertation, realization aspects are thoroughly discussed within two sections. First, the design considerations (Chapter 6) that provides methodologies for implementing extracted design insights based on the developed case studies. Second, within 7.8 which provides an outline realization approach of serpentine-shaped robotic appendages.

1.4   Research Methodology and Dissertation Organization

1.4.1   User-Centered and Participatory Design

Although previous works on SRLs have provided numerous interesting prototypes, these works have failed to capture essential design dimensions for constructing a wearable robot for daily use. We believe most existing research literatures focus on a technology-development perspective; where the presented works emphasize hardware novelty and interesting functionalities, yet fail to fulfil the bigger domain of interaction dynamics, usability challenges, ergonomics that are essential for daily used technologies. From a human-computer-interaction (HCI) perspective, investigating new technologies encompasses a multitude of dimensions that surround usage and adoption of daily used technologies (Gemperle, Kasabach et al. 1998, Lazar, Koehler et al. 2015).

User-centered design (UCD) (Norman and Draper 1986, Earthy, Jones et al. 2012) is an iterative design process and a framework of tools that is applicable to a wide range of domains, like software engineering or the design of product or systems (Lazar 2007, Lazar, Feng et al. 2010). *Participatory Design* (PD) (Muller 2003, Muller 2007) is a UCD process that thoroughly involves users in all stages of the design lifecycle. In PD, users input towards the design process and ownership of the final outcome is more comprehensive than in traditional UCD approaches. The advantage of PD is that it constantly relies on users' feedback for requirements generation, implementation and evaluations, thereby ensuring meeting users' expectations and usage requirements throughout the project. This dissertation adopts UCD and PD as a main investigation approach.

UCD and PD have largely been adopted for designing a variety of products, systems, services and devices. UCD was originally proposed by Norman and Draper (Norman and Draper 1986), where they proposed UCD as an effective methodology for designing products

and services. Accordingly, the versatility of UCD and PD has been shown with numerous works HCI research literatures in the last 30 years, where UCD and PD was utilized in a wide array of interaction design projects, such as to design augmented reality experiences with children (Brun, Ruer et al. 2018), people with special needs (Frauenberger, Makhaeva et al. 2016) and various novel wearable systems (Smailagic and Siewiorek 1999, Zhu, Fjeld et al. 2018). PD has also been increasingly adopted in robotics researches, where it was especially useful for designing social robots (Lee, Šabanović et al. 2017, Reich-Stiebert, Eyssel et al. 2019), like service robots at home (Leong and Johnston 2016) or as wearable SRLs (Vatsal and Hoffman 2017). These research literatures have shown that PD can play a vital role in designing, developing and validating robotic designs and functionalities that rely on realistic user expectations and requirements.

Previous research literatures (Lazar, Feng et al. 2010) identified three essential conditions where PD is especially effective and is superior to other approaches. First, when the task specifications are not fully known (Carroll, Chin et al. 2000). Second, when the situation, or context of use, is not fully understood (Lazar 2007). Third, when minor errors can be critical, such as within airplane systems or nuclear power plants. In comparison to other investigation methods, PD has been shown to be effective for capturing deeper insights from multiple perspectives, such as those surrounding numerous interconnected user requirements, situations, and tasks (Lazar, Feng et al. 2010). In addition, a core aspect of PD is rapid prototyping and evaluations with respect to user's requirements and expectations by using successive prototypes or evaluations focused on definite attributes or objectives (Muller 2007, Duarte, Brendel et al. 2018). This approach allows investigators to quickly evaluate attributes of initial designs prior to full-fledged evaluations, which does not only contribute to reduced time and effort, but also enables designers to iteratively and flexibly experiment with a variety of designs and evaluation methods (Lazar, Feng et al. 2010).
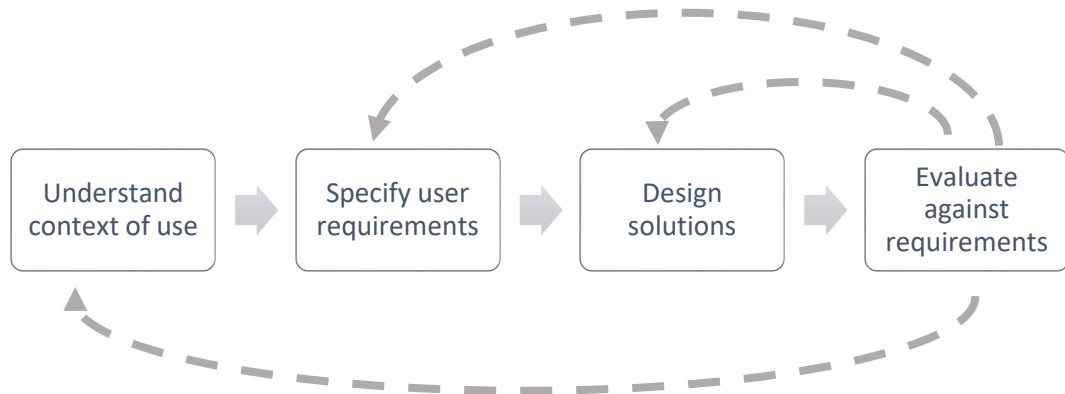
Figure 2 : User-Centered Design approach. The basic iterative processes of UCD are illustrated. UCD is flexible and can incorporate different methods to carry-out each phase (Interaction-Design-Foundation 2019)

Literature survey of existing works within multipurpose wearables and SRLs reveal matching preconditions to the PD approach. First, although previous researchers have proposed intriguing SRL prototypes, the exact usage expectations of such wearables within daily usage contexts are not known. For example, we do not how users would utilize multipurpose robotic appendages on day-to-day tasks. Moreover, the daily usage contexts of multipurpose appendages are unknown, as there are not on the wild field studies or evaluations of systems beyond industrial or laboratory contexts. Secondly, accumulated knowledge from research on daily used wearables (Gemperle, Kasabach et al. 1998, Dunne and Smyth 2007, Lazar, Koehler et al. 2015) and wearable computers (Starner 2001) indicate that designing such wearables encompasses interconnected design attributes; such as

ergonomics, shape, aesthetics and social impact. Such dimensions are not fully understood within mentioned domains and are not explored at all within the domains of multipurpose wearable appendages. Therefore, these preconditions of the research domain as well as the nature of the devices and target audience makes PD a viable option for investigating the design considerations of multipurpose wearable appendages within daily usage contexts.

The research conducted in this dissertation is based the UCD process. The research methodology adopted in this dissertation builds upon the standard UCD process (discussed in section 1.4.1), by including an extra step for analyzing and extracting the various case studies (As shown in Figure 3). The research is conducted iteratively and in accordance to the UCD method.
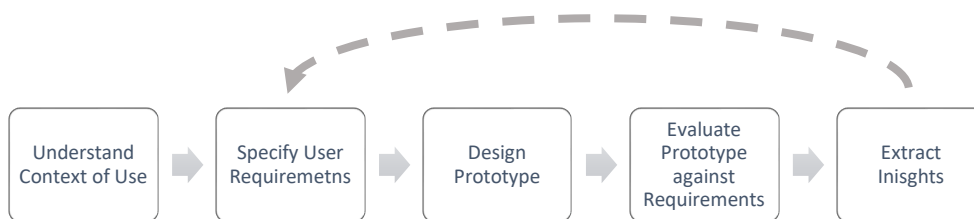
Figure 3 this research follows the standard UCD process, with the addition of an extra step to capture and integrate evaluate insights that would be used for extracting the design considerations

1.4.2 Research Approach

First, we conduct a series of preliminary studies to enable us to understand user related requirements and expectations when using serpentine-shaped robotic appendages within daily contexts, and to understand the potential research challenges. Second, we iterate through a series of case studies, where each case study has a specific design requirements and evaluation objectives. Lastly, the evaluation results of the case studies are combined, analyzed, and presented as a set of design considerations. This process is shown in Figure 4.

A variety of validation methods are used to elicit the insights, which are widely used within UCD and PD approaches (Norman and Draper 1986, Smailagic and Siewiorek 1999, Lazar 2007, Interaction-Design-Foundation 2019). These methods include brainstorming sessions and focus groups (Rosenbaum, Cockton et al. 2002, Hitchens and Lister 2009), surveys (Koelle, Kranz et al. 2015, Alallah, Neshati et al. 2018), user interviews (Kim, Kwak et al. 2009, Kuru and Erbug 2013) and user studies, which where all commonly used within UCD and PD methodologies. The selection of methods was varied depending on the evaluation objectives. Overall, a series of nine studies is conducted that involved participants.
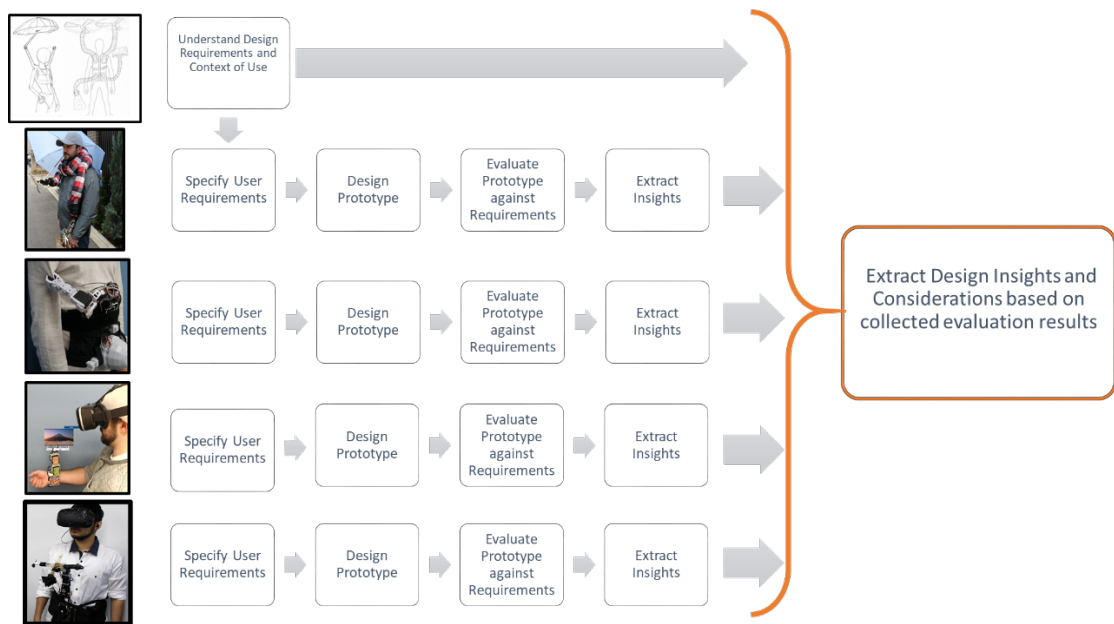
Figure 4 this diagram illustrates the overall research roadmap of this thesis. The process is based on UCD, where we carried out a series of studies to elicit a different insight for designing serpentine-shaped robotic appendages. Lastly, the insights are collected and used to form design considerations that can be used for designing future systems.

1.5   Dissertation Overview

From this section onward, this dissertation is organized as follows: Chapter 2 presents a background of related research and a discussion of such research with respect to the development serpentine-shaped robotic appendages. This dissertation builds upon a myriad of research domains. Accordingly, this chapter starts with a discussion of the methods and challenges of designing interactions and wearable devices that target the daily interaction context. Moreover, the area of shape-changing interfaces is discussed, highlighting prominent differences between the serpentine-shaped robotic appendages and this research domain. Next, we touch upon different domains of wearable systems, including supernumerary robotic limbs (SRLs), kinetic and fashion wearables, and actuated wearables, all of which serpentine-shaped robotic appendages extends various design directions and considerations. This chapter ends with a discussion of the concept of serpentine-shaped robotic appendages and how it relates to the mentioned research domains.

Chapter 3 covers the preliminary studies conducted to address contextual factors and requirements for designing serpentine-shaped robotic appendages. Two user studies are discussed. The first user study is concerned with investigating the requirements and expectations of using serpentine-shaped robotic appendages within daily contexts. The second user study investigates the research challenges and opportunities for designing serpentine-shaped robotic appendages from the perspectives of Robotics and HCI. The outcomes of these studies enabled extracting insights about the main usage requirements, challenges and expectations that were further investigated in the case studies.

Chapter 4 discusses four case studies, their evaluations and analysis. The first case study, called Orochi (section 4.2), builds upon the findings in the preliminary works to establish the design considerations, embody them in a prototype and evaluate them. The second case study, called HapticSerpent, focuses on exploring novel haptic feedback enabled by serpentine-shaped robotic appendages, and follows with an investigation of the

acceptability of receiving various types of feedback throughout the user's body. The third case study, weARable (section 4.4), explores how user experiences can be designed for serpentine-shaped robotic appendages, presenting a design space, an integration architecture and a preliminary evaluation of various user experiences. The last case study, called HapticSnakes (section 4.5), presents a system for delivering novel feedback to users. A design space that comprises dimensions for constructing novel experiences is constructed, followed by two evaluations targeting taps and novel haptic feedback which can be applied to a variety of daily interaction contexts.

Chapter 5 focuses on extracting the insights from the preliminary evaluations and the case studies. Accordingly, these insights categorized, analyzed and presented under three main section to correspond to the first, second and third research questions, respectively. First, daily usage expectations. The data gathered from preliminary studies and the first case study are combined and analyzed to form a use-case distribution comprising 457 use cases, where they are discussed and classified under three primary categories: physical interactions, digital interactions, and others, underlining the requirement of multipurpose use. The second section is concerned with social and user acceptance. Social acceptance comprises challenges in unobtrusiveness, therefore, insights to achieve unobtrusiveness are extracted and discussed case studies. Another aspect is social acceptability, where insights from the case studies highlight several interleaved challenges for public usability of serpentine-shaped robotic appendages. Extracted insights indicate user acceptability challenges in undesired and controversial use cases, as well as undesired interactions. These aspects are analyzed and discussed with respect to the case studies, underlining their importance in contributing to user adoption in future deployments. The third section is concerned with user experience design. Design and implementation insights emphasizing methods of enabling multipurpose user experiences and designing user experiences with multiple interaction paradigms. Moreover, a classification of cross-device digital interactions is provided, citing example implementations extracted from the case studies. Such classification enables designers to identify and implement cross-device user experiences that seamlessly combine serpentine-robotic appendages and various digital devices.

Chapter 6 addresses the fourth research question. We identify a set of design considerations for designing serpentine-shaped robotic appendages targeting daily usage contexts. These design considerations are based on the design, implementation and evaluation of the case studies. We start with an overview of the design considerations and providing a methodology to implement the considerations in a systematic method. The design considerations are classified into four main categories. The first consideration is purpose domain, which is concerned with designating which tasks the designers should consider when creating serpentine-shaped robotic appendages. The second consideration is interaction design, which presents design dimensions and methodologies for constructing cohesive user experiences that cope with user's expectations and multipurpose use. Third, wearability and ergonomics, which is concerned with addressing wearability paradigms that can provide varied levels of flexibility during daily use. Various wearability methods are extracted from the use cases to exemplify the variety of implementation approaches with respect to required flexibility. Fourth, unobtrusiveness and social acceptability, which are mainly concerned with methods to decrease undesired attention when the robot is worn in public, as well as the methodologies to evaluate public acceptance of various public interaction using the robot. We conclude by discussing implementation methods for each design consideration based on the case studies and indicating some trade-offs in embodying the design considerations using serpentine-shaped robotic appendages.

Chapter 7 discusses limitations and future research directions. A number of aspects related to the research questions are discussed. First, the limitations to the domain of

multipurpose use is discussed, as there are unconsidered use cases that fall beyond functional requirements or difficult to extract from a user-centered methodology. For example, using the robot for fashion, hedonic purposes or as a wearable teleoperation platform. Similarly, difficulties in social acceptability presents a number of challenges, some of which bear similarities to those of novel wearable systems. Therefore, established evaluation methods of wearable systems can be the foundation from which social acceptability research about serpentine-shaped robotic appendage are built upon. While the extracted results and insights in this dissertation mainly emphasize serpentine-shaped robotic appendages, the design considerations can be generalized. The design considerations can be realized in different methods, thereby resulting in other intriguing methods of fulfilling the considerations. Further aspects related to the technical implementations are also presented. Most importantly, the need to develop technical considerations that examine the design dimensions from an implementation perspective. Also, aspects related to actuation, mechanical design, safety are also discussed in light serpentine-shaped robotic appendages. The feasibility of implementing wearables based on the presented case studies is discussed, given that the level of fulfillment of the design consideration is relatively scaled down.

Chapter 2   Background

This dissertation builds upon five main research domains: Wearable and interaction design for daily contexts, supernumerary robotic limbs (SRLs), shape-changing interfaces, kinetic and fashion wearables, and actuated and multipurpose wearables. This chapter discusses these domains and how they relate to serpentine-shaped robotic appendages.

2.1   Wearable and Interaction Design for Daily Contexts

Numerous previous literatures investigated various types of interaction methods and devices for daily use. First, some studies investigated mobile contexts of use, where its attributes and specifications, such as user's pose, walking speed and social acceptability, hugely affect the interaction experience (Sears, Lin et al. 2003, Tamminen, Oulasvirta et al. 2004, Barnard, Yi et al. 2006). These attributes are often difficult to clearly define and are found to be very diverse (Sears, Lin et al. 2003, Tamminen, Oulasvirta et al. 2004), dynamic (Oulasvirta 2005), and closely-interrelated (Barnard, Yi et al. 2006). Despite the diversity of previous approaches to develop interactions for the mobile or daily context, the suitability and effectiveness of these interaction methods are essentially dependent on contextual attributes (Kölsch, Bane et al. 2006, Lee, Billinghurst et al. 2013, Wille, Scholl et al. 2014, Grubert, Heinisch et al. 2015). For instance, although hand gestures are powerful for direct digital-object manipulations, they have social limitations during public use and prolonged usage may result in arm fatigue (Hincapi, -Ramos et al. 2014). Therefore, adaptive input systems (Malinowski, K et al. 1993) have been proposed to address the dynamics of daily use, such as to provide dynamic input-method designer for interacting with head worn displays under different contexts of use (Al-Sada, Ishizawa et al. 2016). Such methods allow users to adapt the interface to cope with contextual factors, and therefore provide efficiency or comfort during daily use.

Similarly, the dynamics of daily use present interweaved challenges that a single wearable design cannot address. Therefore, an essential aspect of the vision of wearable computing is adaptability (Sears, Lin et al. 2003, Barnard, Yi et al. 2006); where such system can be adapted to cope with a variety of applications or contextual interaction requirements. Moreover, modern research results provided evidence that users prefer wearing one device

that is capable of a wide variety of purposes, rather than wearing many single-purpose wearable systems (Clawson, Pater et al. 2015).

These indications collectively point out the importance of genericity in daily worn systems, thereby being applicable to a wide variety of contexts. As this thesis emphasizes a daily worn and multipurpose serpentine-shaped robotic appendage, we accordingly defined the scope of multipurpose use, embodied such consideration and evaluated it. Lastly, we identify this concept as a main design consideration of daily worn serpentine-shaped robotic appendages and providing design and implementation insights for future systems.

2.2   Shape Changing Interfaces

Shape-changing interfaces use alterations of physical properties to create various interactive modalities (Coelho and Zigelbaum 2010, Alexander, Roudaut et al. 2018). LineFORM (Nakagaki, Follmer et al. 2015) is a shape-changing interface with serially connected actuators in a serpentine morphology. The high DoFs enable LineFORM to take different shapes, adapting to a variety of interaction contexts, such as becoming a tangible input device or conveying information by taking different shapes. ChainFORM (Nakagaki, Dementyev et al. 2016) presents an extension of LineFORM, which includes input and output methods, along with a user-modifiable snake-shaped structure, which further expand its possible applications.

While our robots, such as Orochi, share some similarities with shape-changing interfaces, like LineFORM, there are fundamental differences. The design space of such works focuses on alterations of physical properties, such as shape, viscosity, or texture, to interface with digital content (Coelho and Zigelbaum 2010). Prototypes, such as LineFORM and ChainFORM, reflect this by being optimized for maximum shape rendering capabilities and flexibility to physically embody and interact with digital entities (Coelho and Zigelbaum 2010, Alexander, Roudaut et al. 2018). In contrast, multipurpose SRLs (Leigh and Maes 2016, Leigh, Denton et al. 2018) and serpentine-shaped robotic appendages essentially augment users' physical interactions with their surroundings, while offering digital interaction possibilities. SRLs and multipurpose SRLS (Bonilla and Asada 2014, Wu and Asada 2014, Leigh and Maes 2016, Parietti and Asada 2016, Leigh, Denton et al. 2018, Saraiji, Sasaki et al. 2018), and accordingly serpentine-shaped robotic appendages (as presented in Chapter 4) include challenges in control, automation, user-robot task coordination, and capable actuation methods to lift or manipulate various daily objects. Such challenges are not as essential for shape-changing interfaces.

2.3   Supernumerary Robotic Limbs

Literature within this area investigates various forms of limbs and associated control and feedback methods in different usage contexts. SRLs were developed for a variety of purposes. Some researchers focused on work-supporting tasks, such as holding components for assembly, drilling holes (Llorens-Bonilla, Parietti et al. 2012, Bonilla and Asada 2014, Saraiji, Sasaki et al. 2018), or supporting the user's body in physically demanding work (Bonilla and Asada 2014). Within professional work domains, a significant portion of robots focuses on supernumerary robotic (SR) arms, which are typically mounted on the user's back (Llorens-Bonilla, Parietti et al. 2012, Bonilla and Asada 2014, Saraiji, Sasaki et al. 2018) or upper arms (Vatsal and Hoffman 2017).

Some works, such as (Wu and Asada 2014), focused on generic grasping and manipulation of physical objects without emphasizing professional work contexts. In this

domain, SR fingers were designed to attach to the user's wrist to augment the hand with further capabilities, such as holding large objects in a single hand or simultaneously holding multiple objects (Wu and Asada 2014). Recent works explored the use of a tail as an extra appendage. These works explored using the tail for self-expression (Kano, Takashima et al. 2017), and to balance the human body or to introduce inertia (Nabeshima, Saraiji et al. 2019) or to use the tail as a seat (Xie, Mitsuhashi et al. 2019) .

Researchers investigated a variety of automation and control methods. Numerous works demonstrated highly autonomous SRLs, where the user did not have to control the robot directly (Llorens-Bonilla, Parietti et al. 2012, Bonilla and Asada 2014, Parietti and Asada 2016, Seo, Shin et al. 2016). Other control and lower automation levels were investigated. Wu and Asada (Wu and Asada 2014) utilized muscle synergies to synchronize the movements of an SR finger to the movements of the user's hands. Other works explored binding the control of an SR limb to a body part, enabling users to manually control the limb by physically moving a designated body part, such as legs (Abdi, Burdet et al. 2015, Saraiji, Sasaki et al. 2018) , hands (Kulu, Vasser et al. 2016) and the head (Kano, Takashima et al. 2017). Control methods including ring-mounted buttons (Hussain, Salvietti et al. 2016), hand-held inertial measurement units (Laha, Bailenson et al. 2016), and arm-mounted electromyography sensors (Hussain, Spagnoletti et al. 2016), were also explored.

2.4 Kinetic and Fashion Wearables

Research within this domain implemented actuation mostly for self-expression and hedonic purposes. For instance, Monarch (Hartman, McConnell et al. 2015) comprises electromyography-controlled shoulder-mounted pleated textile units that retract and expand for self-expression. Similarly, Berzowska and Coelho (Berzowska and Coelho 2005, Clarke, Dunne et al. 2016) integrated shape memory alloys within two dresses, enabling them to move or change shape over time. Additional works attempted to pair expressive and functional aspects within wearables. Scarfy (Von Radziewsky, Krüger et al. 2015) embeds shape memory alloys and a vibration motor within a scarf, enabling it to convey subtle feedback through shape-change and vibration patterns. Similarly, Flutter (Profita, Farrow et al. 2015) is a dress that embeds actuated winglets used for substituting hearing by converting sounds into vibrations. Finally, actuation is used to enhance a wearable's ergonomics, such as for optimal fitting or automatic lacing of (Clarke, Dunne et al. 2016)

This category of wearable systems provides interesting insights towards the design of daily worn serpentine-shaped robotic appendages. Although most of the wearables focus on self-expression and hedonic purposes, their ergonomic and fashion-oriented design makes them generally perceived as typical garments. This ability is essential in decreasing undesired noticeability or social pressure upon wearing such devices. Therefore, we extend this design approach by embodying and evaluating it within the case study of Orochi.

2.5 Actuated and Multipurpose Wearables

This category of wearables presents devices with embedded actuators that enables them to achieve various capabilities, such as shape-changing, haptics or basic physical actions. Generally, many of the wearables use embedded actuators so that they can be applicable to a wider domain of tasks. A notable related work in this domain is by Leigh and Maes (Leigh and Maes 2016) which explored the usability of a shape-changing wrist-worn SRL. Apart from acting as SR fingers, their robot changes shape to become a haptic PC joystick or a wristband by completely wrapping around the user's wrist. Users control the SRL through an

electromyography armband. They additionally presented a reconfigurable SR finger that enabled a variety of interactions through a modular design (Leigh, Parekh et al. 2017). Similarly, Rovables (Dementyev, Kao et al. 2016) is a robotic vehicle that is attached magnetically to the user's clothes. Rovables can travel around the user's body freely and provide different interactions, such as haptic feedback or move user's clothes. In Rovables, the wearable's unique ability to be customized with different modules, combined with the ability to freely travel around user's clothes, allow the wearable to be used for many purposes. Overall, mentioned wearable robots attempt to tackle the complexity of daily use by being multipurpose, thereby underlining the importance of this concept to design daily used wearables in general, and in extension, serpentine-shaped robotic appendages. Accordingly, a variety of our case studies are built around validating and investigating multipurpose use for serpentine-shaped robotic appendages. Section 6.6.1 also specifically discusses multipurpose use and provides several embodiment methods based on our developed case studies.

2.6   Serpentine-Shaped Robotic Appendages

The concept of serpentine-shaped robotic appendages draws from, and extends, research presented within the before mentioned research domains. First, the general design direction of wearable devices indicate the need for multipurpose use (Starner 2001, Dementyev, Kao et al. 2016, Leigh, Agrawal et al. 2018). Although most wearable computer systems, that target daily use, embody multipurpose use to an extent, the multipurpose domain of serpentine-shaped robotic appendages span beyond what have previously been explored. Moreover, unlike works on SRLs which targeted specific physical domains, serpentine-shaped robotic appendages are designed so that they are able to accomplish various physical and digital interactions. Therefore, the concept of multipurpose use is validated through this dissertation from the perspective of serpentine-shaped robotic appendages, first using the preliminary studies, and later through the embodiment of the case studies and their evaluations.

Public usability and wearability are essential aspects of daily use. Various works within fashion wearables target daily wearability by coupling aesthetic and functional aspects. Such coupling allows such wearables to be perceived as garments or accessories, thereby drawing minimal amount of attention. Similarly, Serpentine-shaped robotic appendages build upon such factor, with direct manifestation and evaluation through the first case study (Orochi). However, the design objectives of fashion wearables and serpentine-robotic appendages are different. Fashion wearables are mainly designed for hedonic self-expression purposes, where functional utilization of the wearable is not essential. In contrary, serpentine-shaped robotic appendages are designed with the objective of being functional wearables, thereby being able to carry out different physical and digital interactions. Therefore, embodying a fashionable design is a mean to relieve wearers from potential social pressures associated with wearing a novel wearable, yet the inner system optimizations of both these wearable systems are completely different.

Chapter 3   Preliminary Studies

This chapter covers two main user studies that were conducted to understand the requirements, expectations and usability contexts of serpentine-shaped robotic appendages. Accordingly, this chapter is separated into two main sections. The first section covers the first preliminary study, which is conducted to investigate the challenges and opportunities of SRLs within daily usage contexts. The second section covers the second preliminary study which was conducted to investigate HCI and robotics perspectives toward the research challenges and opportunities of such wearables.

3.1 Investigating the Challenges and Opportunities of Supernumerary Robotic Limbs

3.1.1   Introduction

Supernumerary Robotic Limbs present numerous intriguing interaction opportunities for daily use. Unlike prostheses that replace biological limbs, and exoskeletons that are mostly passive; enhancing innate human capabilities (e.g. allowing users to jump higher (PowerSkip 2018) to travel faster (SpringWalker 2018), SRLs are kinematically independent of the human skeletal structure (Parietti and Asada 2016). Such independence provides numerous interaction opportunities that were not previously investigated.

SRLs can actively perform tasks similar to, or beyond natural human capabilities. Previous works have investigated different forms of SRLs, such as arms (Saraiji, Sasaki et al. 2018), legs (Parietti, Chan et al. 2015), and fingers (Wu and Asada 2014). While there is a large body of work within SRLs and human augmentation communities, such works are limited. First, the vast majority of research, especially within robotics, focused on the technical feasibility of prototypes that mimic human limbs in terms of aesthetics and/or functionality. Second, the majority of works focused on industrial applications that had well-defined contexts, however, daily use constitutes a context that is dynamic and largely unpredictable, therefore, the dynamic daily interaction context (Sears, Lin et al. 2003, Barnard, Yi et al. 2006) is mostly neglected in previous work.

Within robotics research domains, SRLs are a subcategory of robotic arms that could be

worn or attached to the human body. Previous works mainly investigated SRLs that resemble human limbs and focused on physical interactions with different objects (Llorens-Bonilla, Parietti et al. 2012, Wu and Asada 2014, Parietti and Asada 2016, Saraiji, Sasaki et al. 2018). SRL-control methods have also varied, where previous works have investigated flexion-sensor gloves (Wu and Asada 2014), muscle-based electromyography (EMG) (Hussain, Spagnoletti et al. 2016), ring mounted buttons (Hussain, Salvietti et al. 2016), and programming by demonstration (Llorens-Bonilla, Parietti et al. 2012).

The objective of this study is to form an initial understanding of the user expectations regarding SRLs within daily contexts. Therefore, the findings of this work form the first steps in bridging the gap between HCI and the field of SRLs by utilizing focusing groups to probe user gathered challenges and expectations of SRLs.

3.1.2 Methodology

Focus groups are widely used within HCI (Rosenbaum, Cockton et al. 2002, Hitchens and Lister 2009, Kim, Kwak et al. 2009), where they were employed in a variety of set-ups to probe usage of future technologies or to gather usability expectations of a certain system. Similarly, we employed focus groups with the aim of understanding how SRLs could be used within daily contexts. Our focus groups were aimed to answer three main research questions: (1) How can SRLs assist in daily activities? (2) What are the requirements of wearing and using SRLs? (3) What do users want to / do not want to feel through SRLs?

Participants: We conducted two focus groups in Munich, Germany and Tokyo, Japan to understand the users' expectations and concerns with regard to SRLs. Altogether, 15 participants took part (6 females), aged between 23 and 67 years (m= 28.7; SD = 10.8). All participants were familiar with SRLs either through sci-fi media or research literature.

Procedure: Each focus group started by having the users fill the consent and demographic questionnaires. Then, the moderator introduced SRLs by explaining the concept and showing figures and videos from related works (Llorens-Bonilla, Parietti et al. 2012, Wu and Asada 2014, Parietti, Chan et al. 2015, Leigh and Maes 2016). The moderators then guided the participants to emphasize their discussions on four main aspects, each lasting for 20~25 minutes:

> 1- The moderator asked, "If there were no technological constraints, what would be use cases for SRLs?" Participants wrote down a variety of use cases and thoroughly discussed them. Participants were also asked to sketch the use cases (see Figure 1).

> 2. The moderator asked, "How would SRLs help in daily activities (e.g., when you wake up, prepare coffee, go to work, etc.)".

> 3. The moderator asked: "What would be requirements of SRLs (e.g. in terms of aesthetics, form factor, placement, and morphology, etc.)".

> Each focus group lasted for 90 minutes. The sessions were recorded for post-hoc analysis. We collected all descriptions, notes and sketches, after which we clustered and documented the use cases and requirements. Lastly, we analyzed the use cases and requirements for use in subsequent study cases. The results of the use cases, requirements and analysis are presented within the next section.

3.1.3 Results and Analysis

> Based on the research questions presented before, we focused our works to elicit insights about four main aspects: 1) Daily usage scenarios of SRLs. 2) Essential design requirements for realizing SRLs from user's perspective. The analysis methodology is explained in the next sections.

3.1.3.1   Analysis Method

We analyzed the focus group in a similar fashion to previous works (Rosenbaum, Cockton et al. 2002, Hitchens and Lister 2009, Kim, Kwak et al. 2009, Zhu, Fjeld et al. 2018). Focus group results are gathered, clarified and qualitatively analyzed by researchers, where results can indicate a specific direction of ideas or patterns in the participants opinions and ideas. Accordingly, our focus groups were conducted and analyzed by three researchers in Japan and Germany. First, we collected the notes, sketches, recordings of the focus groups. Next, as our focus group was grouped based three main research questions, we analyzed the gathered materials corresponding to teach phase of the focus group in a similar manner to the process proposed in mentioned previous works.

To address the first and second questions, the use cases were extracted from the material by inserting all gathered information into a spreadsheet (As shown in Appendix 1). The data was later formatted and clarified of errors and duplications, after which it was classified based on the ADL categorization (Katz, Downs et al. 1970). We extended the ADL categorization as it is widely used in prosthesis research to describe daily physical manipulation tasks. The third research question in a similar manner. The researchers analyzed the script and discussions raised by the participants, identifying discussion points that participants had longest discussion time about. As participants were asked to sketch their ideal wearable robot, participants were also asked about the main design requirements to justify their proposed designs. The previously collected insights from the discussions were structured and presented as main requirements for designing.

3.1.3.2   SRL Cases of Daily Usage

From the notes and audio recordings, we extracted 169 use cases. The use cases are listed in Appendix 1. These use cases were then clustered into 11 categories by two researchers. Some were clustered into further subcategories. Figure 5 summarize the categories, subcategories, and how many use cases fall into each of the categories. The description of each of the categories is as follows: *Basic physical interactions* cover generic use cases where participants mainly expressed how SRLs can extend physical abilities. These include reaching out for objects beyond arm's reach, or extending physical height (e.g., to look for something on an unreachable shelf). Many reported use cases involved multitasking (e.g., brushing teeth and hair simultaneously).

The *Daily activities* category was inspired by Gerontology research about Activities of Daily Living (ADLs) (Lawton and Brody 1969, Katz, Downs et al. 1970). An interesting subcategory was *Manipulating and Morphing* into tools, where participants gave examples of use cases in which tools can be attached to or be controlled by an SRL (e.g., screwdrivers or hair dryer). Moreover, participants gave examples of SRLs morphing into tools (e.g., umbrella in Figure 1). Another category is *complex and work-related tasks*, which we define as tasks that normally require high proficiency or very specific expertise. This category includes use cases such as operating vehicles or professional equipment (e.g., surgical tools).

Perceptions was another area into which participants proposed various ideas; they suggested that SRLs can amplify human senses or create novel ones. They highlighted how SRLs can allow, for example, sensing temperatures of liquids or environments, or augmenting auditory perception by allowing one to perceive a wider range of frequencies. Other participants proposed enabling sensing chemical compositions of surrounding substances, detecting nearby movements, or embedding biometric sensors to better understand feelings and emotions of others.

Participants suggested *augmenting commuting methods*, for example by having more and stronger legs that allow fast and energy-efficient traveling. SRLs could also facilitate skiing

and moving in snow. In *human-to-human interactions*, participants suggested *enhancing communication*, such as by automatically adapting to cultures with different greetings or translating words to sign language. Furthermore, participants suggested that SRLs could enable *new means to express* one's feelings or opinions. Some suggested a tail based SRL that can be used to express mood or emotions based on the tail's shape or movement (Nabeshima, Saraiji et al. 2019).

A set of use cases are related to using SRLs for personal care and to make the user comfortable. Two participants suggested that SRLs can morph into chairs or kangaroo-like tails that allow the user to sit anywhere. Several suggestions revolved around Safety and self-protection. This included protection from falling while skating or walking and protecting from hazardous trajectories. Other interesting use cases include supporting the disabled, such as sense substitution methods for the blind or as a prosthesis. Also, participants mentioned using SRLs for Human aesthetics (e.g., making the user look taller), and Augmenting sports and creative tasks (e.g., playing different musical instruments simultaneously and assisting in climbing).

3.1.4 Requirements

In this section, we discuss the elicited design and usability requirements based on the focus groups.

3.1.4.1 Multipurpose Use

The analysis of the elicited use cases and requirements indicate that being multipurpose is a core requirement for SRLs. Such finding re-emphasizes previous findings from research about wearables (Starner 2001, Clawson, Pater et al. 2015, Lazar, Koehler et al. 2015). We further classify this requirement into:

1- *Morphological Design and Context Awareness:* the overall shape of SRLs should change to fulfill different contextual requirements (e.g., morph into a tool as in Figure 6).One participant suggested that *"[based on the context], it can adapt to what you need, it can fold to become two arms, or join together to become like a stick"*. SRLs should also be exchangeable/customizable based on task's needs. Our participants suggested exchangeable end-effectors (e.g., a gripper or a tool can be attached to the tip of an arm).

2- *Extendable SRLs:* one requirement is to augment standard SRLs with tools, sensors, digital Inputs/Outputs (I/Os) and features beyond SRLs physical interaction capabilities. Participants suggested embedding 1) tools: clock and cutlery; 2) sensors to enable novel senses; 3) digital I/Os and features similar to smart phones. SRLs should allow interaction with digital content and the environment.

Overall, reported use cases indicated how multipurpose SRLs can be realized in daily usage contexts. While previous work reported that SRLs should not replace a user's natural capability (Leigh and Maes 2016)(e.g. to replace their arms or fingers when manipulating objects), we found that fully autonomous SRL tasks are desired (e.g., cooking or driving). Such finding opposes previous design direction (Leigh and Maes 2016), therefore, future works should investigate whether some innate capabilities can be replaced by such wearables, especially in tiresome and complex tasks.
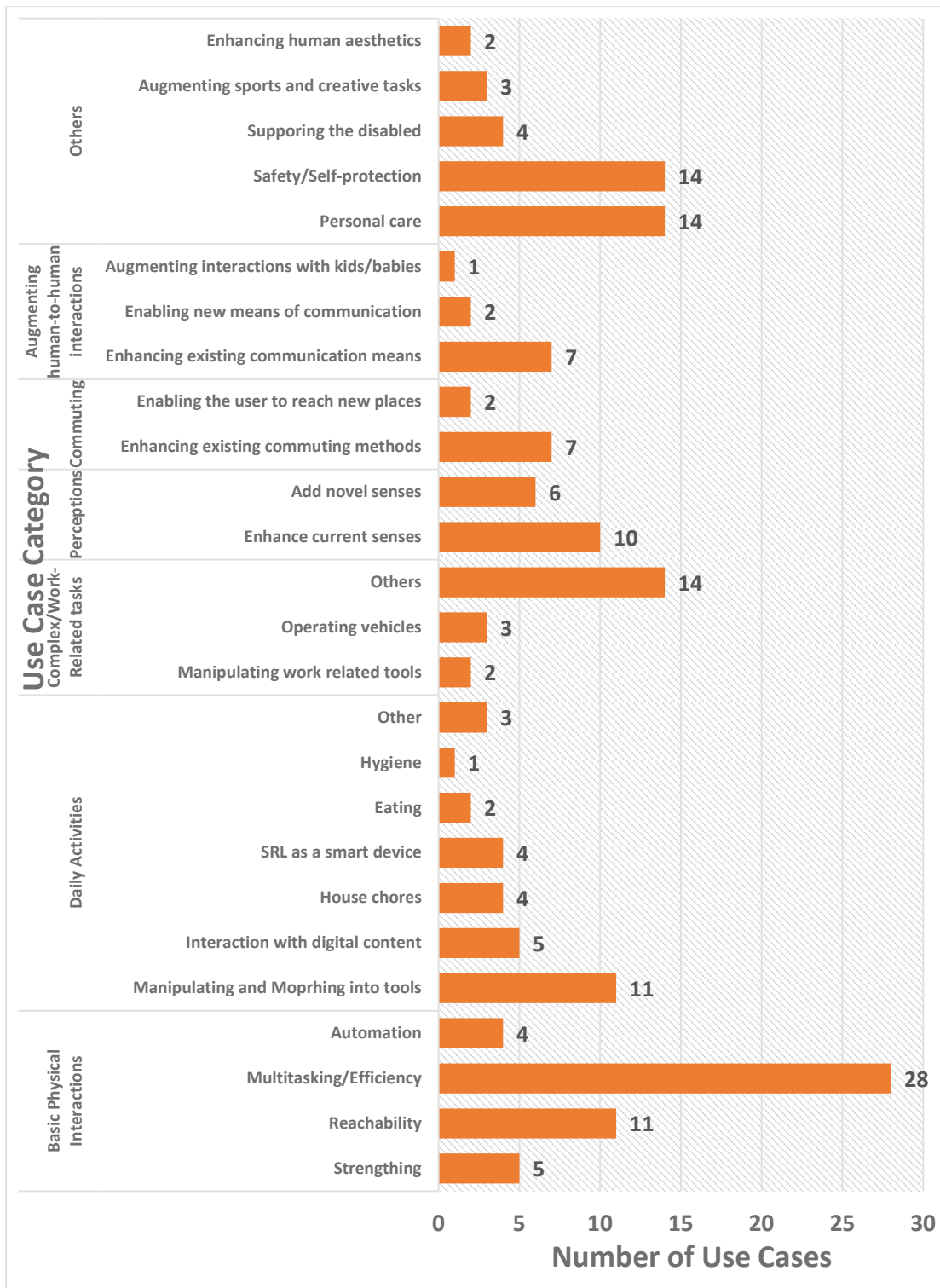
Figure 5 this diagram shows the use case distributions. Most use cases where in the categories of basic physical interactions and Daily activities. Participants proposed intriguing use cases to enhance human aesthetics and in augmenting human-to-human interactions.
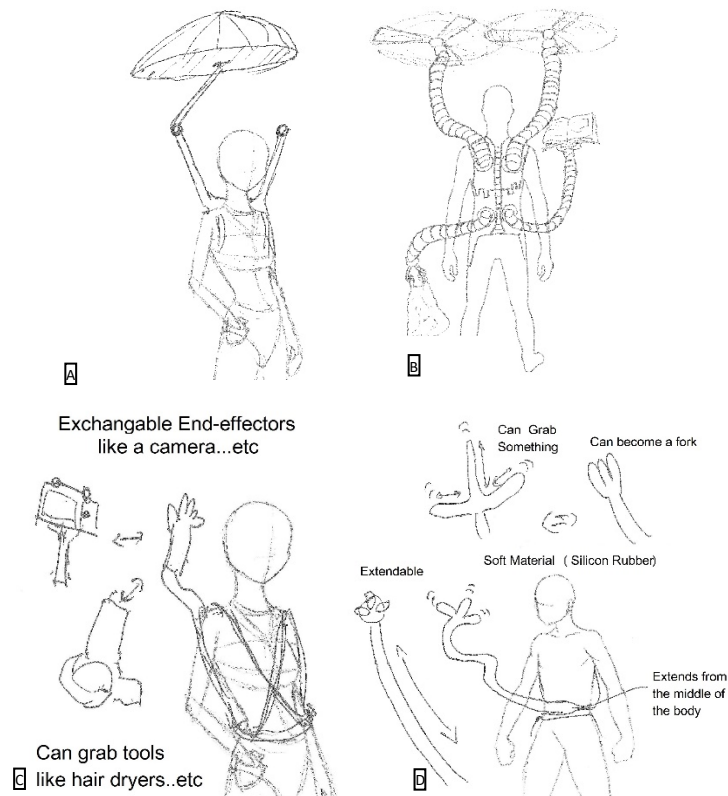
Figure 6 (A)(B) users sketched how a daily worn SRL should look like, where they envisioned the wearables as capable of various functionalities. (C)(D) Users proposed intriguing methods to increase SRLs usage domain within daily use, such as the ability to exchange or to morph to different end-effectors.

3.1.4.2   Perceptions

While some of the aforementioned requirements were partially discussed in prior work, we additionally present novel requirements unveiled in the focus groups. Participants stressed that appendages should support:

1- *Controlled Sensory Feedback:* participants mentioned they would like to feel the state of an SRL's at different conditions and thresholds. For example, participants mentioned that perceiving the degree at which SRL-joints are bent without visual contact with an SRL (similar to proprioception). Participants also indicated that the ability to sense the surrounding environment through an SRL is essential. For example, to feel a surface's texture or temperature. However, participants believed such sensations fit certain sensory thresholds as to not hurt the wearer or cause discomfort during usage. For example, when touching an extremely hot object, the temperature values should be transformed and delivered to user's without causing discomfort. Moreover, sensory augmentation by substitution (Bach-Y-Rita, Collins et al. 1969) was also suggested, for example, transforming a surface's temperature to different levels of haptic feedback. Therefore, we believe sensory feedback plays an essential role in the usability of SRLs, where the intensity and type of feedback should be carefully designed.

2- *Enhanced Perception:* SRLs should not only enable but also enhance user's perceptions, but also enable extending our perception and sensing abilities. For example, to equipping an SRL with a camera for endoscope-style controls, auditory perception enhancements to filter or amplify different voices, and olfactory sense

extensions to protect from harmful gases.

3- *Novel Senses:* participants reported that SRLs should augment users with novel senses. For example, using built-in sonars that allow navigation in the dark similar to bats, automatically detecting people's emotions, and sensing chemical substances through sensors, such as to detect the taste of food.

We believe that participants regarded sensing and perception to be among the multipurpose functions SRLs should deliver. This is also supported by the large number of use cases that involve enhancing existing perceptions and/or enabling new ones (Figure 5)

3.1.4.3   Aesthetics and Wearability

Participants also reported non-functional requirements that effected the design of a daily worn appendages, which we summarize as the following:

1- *Comfort and Fit*: Similar to fashion wearables (Profita, Farrow et al. 2015), SRLs should be ergonomic, easy to wear and take off, comfortable, and lightweight. While such design requirement was not thoroughly discussed in the current study, we believe that such requirement is essential to enable daily use. For example, participants have shown various designs with wearability methods and locations, such as strapped to the user's back, chest or feet.

2- *Aesthetics and anthropomorphism:* SRLs should be personalizeable in terms of colors, designs and features. Robot-like limbs were mostly preferred over anthropomorphic limbs (i.e., human-like limbs) by our participants, citing reasons such as being "creepy", "scary" and "unnatural". Interestingly, one participant preferred humanlike limbs and found robot-like ones to be "scary".

3.2   Investigating Design Requirements and Challenges from Robotics and HCI Perspectives

3.2.1   Introduction

Designing robotic wearables like serpentine-shaped robotic appendages comprise research challenges that span multiple research domains. From a hardware perspective, serpentine-shaped robotic appendages are robotic wearables, comprising mechanical structures, actuations and controls optimized for wearability and daily usage. From the wearable's perspective, serpentine-shaped robotic appendages can be classified as wearables with robotic components that enable a variety of daily interactions. Therefore, we identify two fundamental research domains that are related to serpentine-shaped robotic appendages, *robotics* and *human-computer-interaction* (HCI).

This preliminary evaluation focuses on eliciting basic research challenges and requirements, tackling both robotics and HCI. Accordingly, we conducted two focus group with expert researchers in robotics and HCI with the objective of understanding the underlying research challenges and considerations needed to design daily worn snake shaped serpentine-shaped robotic appendages. The focus group outline, procedures and results are discussed within the next subsections.

3.2.2   Focus Groups

We conducted two focus groups involving 14 participants, taking place in Germany and in Tokyo. Each focus group emphasized one perspective, the focus group in Tokyo addressed the robotics perspective, while the one in Germany addressed HCI challenges. The HCI focus groups was conducted with a total of 7 participants, including 5 PhD students, 1

Postdoc and 1 Professor. All participants were actively conducting research in various HCI domains. The robotics focus group was conducted with 7 participants, all of whom were active researchers of various domains in robotics. The group included 2 professors, 1 postdoc and 4 PhD students. The procedure was conducted in the same manner for both focus groups. The objective of the focus group is to understand essential research requirements, challenges and considerations from both robotics and HCI perspectives.

3.2.3 Procedure:

The procedure starts by having the participants sign the consent forms, after which they had to fill out demographic information. Next, we introduced the topic of robotic appendages and supernumerary robotic limbs, showing pictures and videos from sci-fi and pop-culture. After that, we carried out the focus groups in two phases. Phase one started by asking participants "*what are the possible research questions (from your perspective) that need to be answered when designing and implementing such systems?"*. This phase lasted for around 30 minutes and included various discussions.

Phase two started was carried out by showing the participants six prominent case studies in wearable robots, some of which resembled basic appendages (Nakagaki, Follmer et al. 2015, Dementyev, Kao et al. 2016, Leigh and Maes 2016, Nakagaki, Dementyev et al. 2016, Gong, Li et al. 2017, Leigh, Parekh et al. 2017). We asked participants to discuss possible dimension and design considerations and asked them what essential challenges they would face if they conduct research on a similar wearable device. Accordingly, we allowed 5 minutes of discussion focused on each presented work. We recorded the participants' discussions and collected their notes for our analysis. Overall, each focus group lasted for 90 minutes.

3.2.4 Results

3.2.4.1 Analysis Method

The analysis method was conducted in a similar fashion to the previous study. First, the gathered audio recordings and notes were filtered and classified based on the conducted on the participants groups. Next, two researchers, in Japan and in Germany, grouped each discussion point based on the scripts of each focus group, where the main arguments and insights were summarized. Specific direction of ideas or patterns in the participants' opinions and ideas was finally analyzed.

3.2.4.2 HCI Perspective

HCI researchers have indicated a number of factors that were essential for designing serpentine-shaped robotic appendages. First, *social acceptability* was discussed, where various participants thought that it is a challenging aspect of such wearables, since they should be socially acceptable. The second aspect is *control and learnability*. As the demonstrated systems were mainly manually controlled systems, such controls seemed difficult and sophisticated to learn for users. Participants proposed various methods to ease the learnability and use of serpentine-shaped robotic appendages with manual controls, such as by building serpentine-shaped robotic appendages that can guide users on how to use them, or to integrate control methods similar to those used to control innate limbs (e.g. using a direct interface with the human neural system).

Next, a variety of ideas were discussed regarding the user experience. First, designing a *cohesive user experience*. Participants though the device should not interfere with daily activities that the user is carrying. For example, if the user is carrying objects, the serpentine-shaped robotic appendages should be smart enough not to hinder the user. Another hindrance could also be raised unexpectedly by the serpentine-shaped robotic appendages. For instance, when it is worn in a way that it blocks the wearers hand movements. Participants

though the serpentine-shaped robotic appendages should be designed in a way not to cause such issues. Moreover, Participants believed that an essential factor of interaction with serpentine-shaped robotic appendages is conveying its status. The lack of input or output methods meant it was difficult to know what was going on with the robot. Moreover, if the robot is multipurpose, it would be difficult for users to deduce which mode of control or interactive experience the robot is currently in.

Aesthetic aspects where also discussed. Participants though that an interesting research question is to investigate whether people prefer human like serpentine-shaped robotic appendages, such as being covered with silicon and colored like a human hand similar to prosthesis, or to prefer robotic looking ones. Choosing human-looking ones (anthropomorphic looking) could also raise issues like uncanny valley (Pollick 2010).

3.2.4.3 Robotics Perspective

Similar to the HCI group, robotics researchers have provided numerous design insights from the perspective of robotics. Participants thoroughly discussed the challenge of *power source*, which was especially essential for wearable robots that are expected to function for prolonged periods of time without access to power. Therefore, addressing the *power source* challenge is one of the most important aspects to realize serpentine-shaped robotic appendages. Moreover, the more capable a robot is, the more power demanding it would be. Manipulating heavy objects requires using actuation methods capable of high torque, which would eventually require sufficient power source.

Safety is another concern of wearable robots. One participant asked, *"How can we ensure safety of a wearable robot?",* and other participants raised several potential methods to address safety. They proposed a number of solutions, for example, by using soft robotic structures, low torque servos or decreasing the number of actuators. However, participants believed that safety should be thoroughly researched from the perspective of serpentine-shaped robotic appendages. *Sensing* is another discussed aspect with respect to the case studies. For example, they proposed using extra sensors, such as tactile sensors, which are required for precise physical manipulations. Lastly, they additionally raised several shortcomings of having robots with high DOF, where they indicated that controlling such robots may be very challenging due to the high DOF, therefore, a certain level of autonomy is required to ease end-user control during real world scenarios.

One of the most important aspect is regarding the design methodology. Participants emphasized the importance of clearly defining the intended tasks, as any robot should be designed based on a specific set of clearly defined objectives and requirements. These design requirements can then be transformed to mechanical design and actuation requirements and attributes in the final robot. The objectives can also be used to define the efficiency of such robot within a variety of usage contexts.

3.3   Conclusion

Overall, we believe that the focus groups have provided important insights about the requirements, expectations and challenges for designing and realizing serpentine-shaped robotic appendages. The first focus group revealed inspiring use cases and expectations from daily worn appendages. These results were categorized and analyzed, resulting in a use case distribution and requirements that are essential for daily use. We discussed how our results compare to previous work, identified novel requirements, and confirmed that some existing ones are also desired by users. Most importantly, the results provide an initial understanding of how a daily worn appendage could be used on day to day basis, which was not previously

studied or understood. Therefore, we build on these results, by embodying the design insights of multipurpose use and unobtrusiveness in the first case study (Orochi, section 4.2), and follow with an in-depth evaluation to deepen our understanding of these design factors. Moreover, we reanalyze the results of this focus group in light of all extracted insights, and discuss them in Chapter 5.

The second focus group results revealed essential considerations that we have to address within the design and implementation of the subsequent case studies. From an HCI standpoint, the seamless of the interaction experience, acceptability during public use are fundamental research questions that are addressed within this dissertation, specifically in section 4.2.2.3 and section 6.5. From a robotic standpoint, essential insights were extracted about the design process of serpentine-shaped robotic appendages, which must be based on well-defined objectives and requirements. Accordingly, we extract numerous requirements from the previous preliminary study, and thoroughly investigate the tasks and objectives serpentine-shaped robotic appendages are expected to accomplish within daily scenarios in sections 4.4 and 6.3.

Chapter 4   Case Studies

4.1   Implementation Scope and Overview

This section presents a series of case studies that were developed to investigate and validate various design domains for realizing serpentine-shaped robotic appendages. Therefore, the design and implementation and validation of the case study is specifically carried out with the objective of addressing the research questions, as discussed in section 1.2 and shown in Figure 1.

The rational for the above development direction is mainly based on two reasons. First, the context of use and design requirements for realizing serpentine-shaped robotic appendages are not investigated in any previous researches. Therefore, designing comprehensive prototypes requires significant analysis of several factors, such as the mechanical design, control, automation and interaction methods. These factors should be optimized based on specific usage objectives (Jacob, Sibert et al. 1994, Beer, Fisk et al. 2014, Ojuroye, Torah et al. 2016), which are in turn largely unexplored within daily used serpentine-shaped robotic appendages. Second, this dissertation uses UCD approach, which iteratively enables rapid design and evaluation of successive prototypes, each focusing on definite design requirements or criterion. Therefore, UCD enabled exploring, investigating and validating prototypes based on various design requirements. Accordingly, extracted knowledge from the series of evaluations, using the case studies, are used to construct an overall understanding of the design considerations required for realizing daily used serpentine-shaped robotic appendages.

This chapter presents and discusses four main case studies from which we use to extract the design insights and the design considerations. First, Orochi, which is a multipurpose serpentine shaped appendage that fulfills three main design considerations: 1) multipurpose use, 2) wearability by context, 3) unobtrusiveness during public use. Orochi is used as a platform to validate and investigate its design considerations for applicability within daily usage contexts. The second case study is HapticSerpent, which is a waist-worn serpentine shaped robot capable of delivering a variety of haptic feedback. HapticSerpent is used to investigate the user acceptability of receiving haptic feedback on various body

locations. Third, weARable, which is a wrist-worn serpentine-shaped robotic appendages that can deliver different interactive experiences. This mainly investigates novel cross-device interactions between a wearable robot and AR HMD, and embodies an approach to provide a user experience that enables multipurpose use. Fourth, the HapticSnakes is a system comprising two serpentine-shaped robotic appendages. This system is used to thoroughly investigate the potential of providing various feedback methods, including haptic feedback, using serpentine-shaped robotic appendages.

4.2 Orochi

4.2.1 Introduction

Supernumerary robotic limbs (SRLs) (Parietti and Asada 2016) are wearable robotic limbs that augment humans. Unlike exoskeletons, which amplify muscular capabilities or prostheses that replace missing limbs, SRLs enhance humans with entirely new limbs. Their kinematic independence from the human skeletal structure allows them to be used in conjunction with natural limbs and they can perform tasks automatically.

In contrast to research on wearable devices, such as smartwatches and wristbands, research on SRLs remains in its infancy. The current research is limited in terms of investigated form factors, interaction, and ergonomic requirements for daily use. For example, most SRLs emphasize novelty in control, feedback, and mechanical design (Wu and Asada 2014, Parietti and Asada 2016), while focusing mainly on physical manipulation of surrounding objects. Previous studies provided evidence that users prefer multipurpose over single-purpose wearables (Clawson, Pater et al. 2015). Therefore, an SRL worn daily should include additional interaction capabilities to increase its value for use. SRLs face these same challenges which impede the realization of mainstream wearables. To the best of our knowledge, no previous work has investigated multipurpose SRLs that address challenges in wearability and everyday multipurpose use.

In this project, we introduce Orochi, a novel multipurpose wearable supernumerary robotic limb developed with three design considerations: Orochi is 1) multipurpose, 2) wear by context, and 3) unobtrusive in public. Our system comprises a serpentine (snake-like) morphology with 25 degrees of freedom and two end effector types. To evaluate Orochi, we conducted two evaluations that focused on a different aspect: 1) How can Orochi be used within daily contexts? 2) How is Orochi perceived when used publicly?

We carried out a series of four hands-on focus group to evaluate Orochi's design considerations. Orochi offers multipurpose use by being applicable in a wide variety of interaction contexts as demonstrated by participants of the four focus groups and multiple sample applications that we implemented. Its flexibility allows it to be worn conveniently in multiple arrangements and locations, and makes it easily removable, which was also confirmed in our focus groups, thus satisfying the second design consideration. As confirmed by our focus group, by retracting and blending in with the clothes, Orochi remains inconspicuous in public as it is perceived as a garment, hence satisfying the third design consideration. We implemented several sample applications of Orochi based on the results of the focus groups, including using Orochi to retrieve objects, as well as interacting with devices, such as smartphones and virtual reality (VR) headsets. Our analysis of the focus group results shows that the versatility of Orochi can enable unexpected and demanding uses, and its wearability and unobtrusiveness where highly valuable traits for daily use

Our second evaluation investigates Orochi is perceived when sued publicly. Therefore, we conducted a survey involving 40 participants to evaluate Orochi's use in public. Orochi was

thought to be unobtrusive, especially when retracted, which indicates that people generally approved of its design. However, participants raised concerns about the effects of Orochi's novelty, which could draw undesired attention when in use. In light of our results, we ended with a discussion about the implications and future research directions for designing this form of wearables.

4.2.2   Design of Orochi
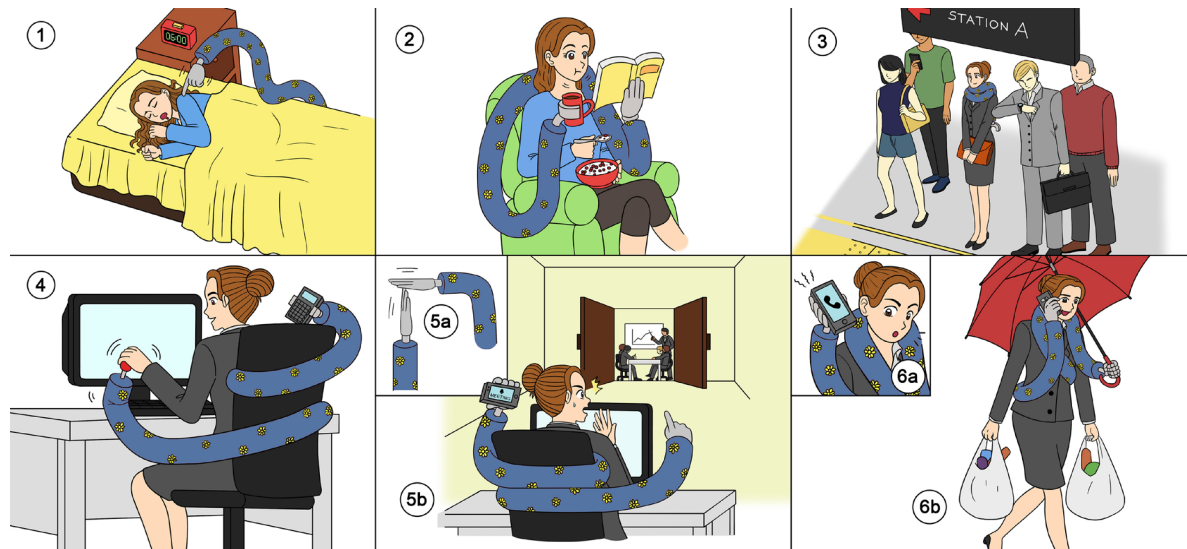
Figure 7 (1) In the morning, Orochi crawls to the user and wakes her up. (2) Later, Orochi helps her drink and read a book while she is having breakfast. (3) While commuting to work, she wears Orochi like a scarf to keep it unobtrusive. (4) At work, she wraps Orochi around the chair where it can assist her by grabbing objects on the desk with one end, while the other end functions as a PC joystick. (5a) Orochi alerts her of a meeting by showing the "timeout" sign, then (5b) showing her the meeting information and pointing to the meeting room. (6a) while holding bags and walking home, she receives a phone call, but since her hands are occupied, Orochi answers the call and (6b) positions the phone at her ear.

In this section, we describe the primary design considerations that motivated the design of Orochi. They are based on a literature survey that identified opportunities and limitations of state of the art SRLs and actuated wearables. We present a serpentine actuated wearable that embodies our design considerations, and we called it Orochi. Figure 7 demonstrates how Orochi may be used throughout the day. We discuss each design consideration and its embodiment.

4.2.2.1   *Multipurpose Use in Daily Interaction Contexts*

Previous approaches emphasized the need for multipurpose daily wearables. For example, Clawson et al. (Clawson, Pater et al. 2015)and Lazar et al. (Lazar, Koehler et al. 2015) suggested that having several wearables for different uses is not desirable, underlining the need for multipurpose wearables. Most importantly, the analysis results from the preliminary studies (3.1.4.1) strongly indicate that potential users of robotic appendages regard multipurpose use as a main requirement. However, few works investigated multipurpose SRLs (Leigh and Maes 2016, Leigh, Parekh et al. 2017). Therefore, our wearable was designed to maximize the spectrum of applications within daily interaction scenarios. We classify daily interaction scenarios into the following categories:

A) *Interactions with Physical Surroundings:* This entails two aspects: First, physical manipulation of surrounding objects is an essential capability for wearable robots, especially for SRLs. The context and purpose of such interactions vary. For example, SRLs can augment the user's ability to manipulate objects that are too heavy, too large to hold in one hand (Wu and Asada 2014), beyond arm's reach,

or dangerous to handle, such as chemicals (AlSada, Khamis et al. 2017, Vatsal and Hoffman 2017). Second, SRLs should enable multitasking by allowing users to manipulate objects without using their hands. For example, an SRL could open a door while the user's hands are occupied (Leigh and Maes 2016, AlSada, Khamis et al. 2017). Repetitive and mundane tasks could also be handled by SRLs, such as opening and holding an umbrella.

B) *Digital Experiences:* Along with physical interaction with the real world, wearable robots can feature a myriad of sensors and mechanical components that can connect users to digital services (Profita, Farrow et al. 2015, Dementyev, Kao et al. 2016, Leigh and Maes 2016). We highlight the following experiences that are promising for wearable robots:

C) *Haptic experiences:* Some wearables that include sensors and actuation methods can sense and exert forces, and can thereby serve as wearable haptic interfaces. Previous research demonstrated various applications, such as a haptic input device for a range of applications (Ion, Wang et al. 2015, Je, Choi et al. 2017, Je, Rooney et al. 2017) and providing haptic feedback to various body parts.

D) *Shape-changing experiences:* Physical morphing of the wearable can be utilized to convey information (Von Radziewsky, Krüger et al. 2015)], for example, to present an icon resembling a specific state or condition (Nakagaki, Follmer et al. 2015, Profita, Farrow et al. 2015).

Implementation of Multipurpose Use in Orochi

Orochi has two types of end effectors, enabling it to physically interact with objects (0Figure 7.2) and multitask in a variety of ways (Figure 7.6b). Orochi can deliver haptic sensations or feedback by applying forces to different areas of the body using these end effectors (0.1). The flexibility brought by many DOF also allows Orochi to take various shapes that can be used for different interactions (Figure 7.5a and 5b).

4.2.2.2   Wearability by Context

Gemperle et al. (Gemperle, Kasabach et al. 1998) defined wearability as the active relationship between the wearable's physical shape and the wearer's body. This concept covers many factors, such as a device's weight, shape, ergonomics, thermal insulation, and moisture wicking (Clear, Morley et al. 2013, Chin 2015). We apply the term wearability by context to refer to the following two factors:

A) *Easy attachment and detachment:* This design factor refers to the wearable's capability to be easily and quickly worn or removed without much effort, similar to everyday garments. The user should be able to switch between attached and detached use in different contexts conveniently. For example, users can quickly take off the wearable and use it to interact with objects from a far (AlSada, Khamis et al. 2017) or as an external input device (Leigh and Maes 2016).

B) *Adaptive attachment*: The wearable should be flexible enough to be worn in multiple locations on the body and in various configurations. In addition to contributing to comfort, this capability allows the wearable to have a dynamic workspace around the user's body, which enables the user to extend a limb in any direction.

The combination of the above two factors allows Orochi to be easily utilized in different configurations around the user's body, as well as when detached from the user's body. This capability enables Orochi to be applicable to a wide variety by adapting its limber body.

A significant problem with some previous wearable robots and SRLs is they are cumbersome to wear and remove. All surveyed implementations rely on strapping mechanisms for attachment to the user's body (Bonilla and Asada 2014, Wu and Asada 2014, Leigh and Maes 2016, Parietti and Asada 2016, Vatsal and Hoffman 2017). Although they are stable, we argue that they are tedious for the user to attach, especially with larger robots, and they may require multiple persons to assist in affixing them (Llorens-Bonilla, Parietti et al. 2012, Bonilla and Asada 2014, Parietti and Asada 2016). Furthermore, strapping the robot to one location prevents it from being easily and quickly fixed to another location. Such adjustability is important for increasing the possible uses of an SRL. For example, fixing an SRL to the user's right arm confines possible interactions to the accessible space surrounding that arm, hence limiting its use on the left, front or back of the user where it might be needed.

Implementation of Wearability by Context in Orochi

Orochi extends the serpentine morphology to realize our wearability objectives. Users can wear Orochi in multiple configurations by simply wrapping it around the body (Figure 7.6b). To remove it, the user unwraps the robot. Orochi can also be used while wrapped around other objects, such as a chair (Figure 7.4). With various wrapping postures, Orochi's end effectors can access and manipulate objects anywhere around the body (Figure 7.2), thereby making Orochi more applicable for *Multipurpose use*.

4.2.2.3   *Unobtrusiveness in public*

As proposed in fashion wearables (McCann, Hurford et al. 2005, Profita, Farrow et al. 2015, Profita 2016), we believe that the coupling of aesthetic and functional aspects is an important factor in designing wearables for daily use. Such coupling not only aesthetically enhances the wearable, but also decreases the social pressure associated with devices of novel form factors (Shinohara and Wobbrock 2011, Profita 2016), making them less noticeable when publicly worn or used. Despite the novel contributions of previous work on SRLs, many of them are quite obtrusive, especially when considering public and daily usage contexts. For example, publicly wearing an SR arm similar to the ones in surveyed works would draw undesired attention due to the bulkiness of the robot, abnormality, and novelty when manipulating objects. We therefore set the following requirements to realize sufficient efficiency, comfort, and appearance.

A) *Inconspicuousness:* The wearable should resemble a garment in its shape and *appearance. This concept builds upon previous ideas from fashion wearables* for daily use, which emphasize the coupling of aesthetic and functional design aspects (McCann, Hurford et al. 2005, Profita 2016). Aesthetic considerations of a wearable also contribute to its unobtrusiveness. For example, several investigated prototypes take the shape of everyday garments, such as a belt (Dobbelstein, Hock et al. 2015), piece of jewelry (Miner, Chan et al. 2001), or wrist watch (Rekimoto 2001). Such wearables are mostly inconspicuous and indistinguishable from socially acceptable garments.

B) *Retractability:* The wearable should be easy to fold away from the user's interaction space. For example, an SRL used as an arm (e.g. (Vatsal and Hoffman 2017, Saraiji, Sasaki et al. 2018)), is unable to retract due to its fixed location and mechanical design, which often leaves the arm protruding from the body even while inactive. In addition to the obtrusiveness, unused yet fully extended SRLs can be dangerous, as they can collide with the surroundings or the wearer's limbs.

Implementation of Unobtrusiveness in Orochi

Orochi is covered with a typical garment fabric, and since it has a limber body, it looks

like a scarf, stole, or a belt when worn (Figure 7.6b). This makes Orochi comfortable and fashionable while contributing to its unobtrusiveness. The flexibility of the serpentine morphology allows both its arms to easily retract and wrap around the user's body when not in use (Figure 7.3).

4.2.3 Realization of Orochi

4.2.3.1 Implementation Objectives

Orochi's implementation has two main objectives. First, to demonstrate how the design considerations can be embodied within a wearable robot. Second, to enable us to validate our design considerations and fulfill our evaluation objectives. Therefore, Orochi was developed with maximum flexibility, so that it fits as many usage scenarios and contexts as possible, while also being capable of demonstrating actual usage. Our rationale for this design decision is that constructing an optimal robot requires significant analysis of several factors, such as the mechanical design, control, automation and interaction methods. These factors should be optimized based on specific usage objectives, which are largely unexplored within daily used SRLs. Therefore, we maximized Orochi's flexibility to gain insights about SRLs' daily usability, wearability, and unobtrusiveness, which would offer valuable insights for designing and validating future robots against specific daily usage expectations (Angeles and Park 2008).

4.2.3.2 Realization of the Design Considerations

As discussed in 1.3.2 Research Emphasis and Assumptions, Snake robots have long been investigated within robotics communities (Hirose and Morishima 1990), where their flexible structure allows them to be versatile across a wide range of domains (Hirose and Morishima 1990, Erkmen, Erkmen et al. 2002). Therefore, we implemented Orochi as a serpentine robot with 25 DOF and two end-effector types. While Orochi is not the first serpentine robot, it is the first to use the snake form factor to realize our design considerations and to be used as a multipurpose daily worn SRL. We used Orochi's versatile design to embody our design considerations as the following:

4.2.3.3 Realization of Multipurpose Use in Orochi

Orochi has two types of end effectors, enabling it to physically interact with different objects; it can be user controlled or teleoperated to multitask in a variety of ways (Figure 8 c, d and e, Figure 14). Orochi's end effectors can be used as always available haptic interfaces with devices like head-mounted displays. The flexibility brought by many DOF also allows Orochi to take various shapes for conveying information (Figure 8 c).
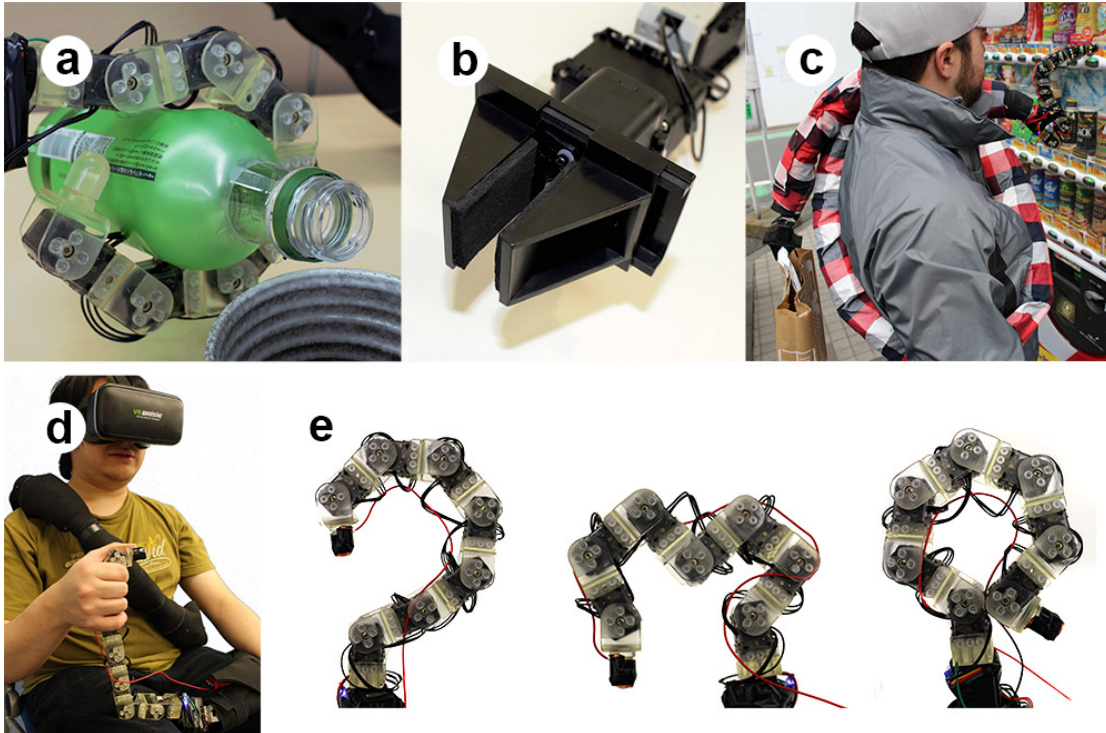
Figure 8 a,b) Orochi is equipped with two different end effectors, c) where they can be used to augment user's interactions in different ways. (d) Its end-effector can be used as a haptic input method, such as for VR, e) or take different shapes, such as "?", "M", or "Q" to convey information.

4.2.3.4   Realization of Wearability by Context in Orochi

Unlike previous works that rely on straps, Orochi uses the serpentine morphology to realize our wearability objectives. Users can wear Orochi in multiple configurations by simply wrapping it around the body (Figure 9). To remove it, the user unwraps the robot. With various wrapping postures, Orochi's end effectors can access and manipulate objects anywhere around the body, thereby making Orochi more applicable for multipurpose use.
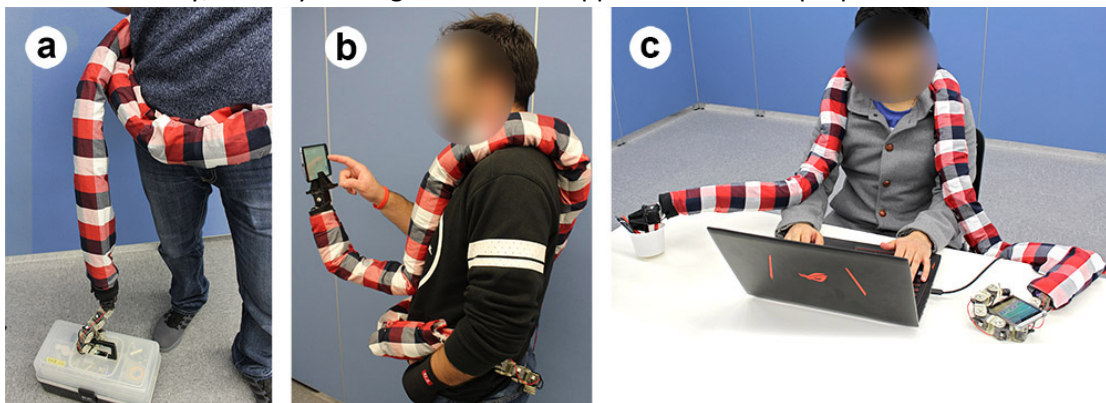
Figure 9 Orochi can be worn differently by context, such as a) around the waist to access objects below, b) above shoulders to hold a smartphone, or c) around shoulders to manipulate surrounding objects.

4.2.3.5   Realization of Unobtrusiveness in Orochi

Orochi is covered with one layer of rubber foam and one textile layer. Since it has a limber structure, it looks like a scarf or a belt when worn (Figure 10), making Orochi comfortable, fashionable and contributing to its unobtrusiveness. The flexibility of the serpentine

morphology allows both of its arms to retract easily and wrap around the user's body when not in use (Figure 10 b,c,d).

Figure 10 a) Orochi is covered by two layers, contributing to comfort and improved aesthetics. b,c,d) Orochi's can be worn in different ways, resembling common garments.

4.2.4 Robot Structure

Orochi consists of a chain of Robotis Dynamixel servomotors (Robotis 2019). The length is adjustable to suit individual preferences by adding or removing motors and extruded aluminum profiles. We tested different lengths and chose a 240 cm long version with 25 DOF, weighing 1.4 kg (Figure 110), with a configuration that is easily wrapped around the user's body in multiple ways. The structure of Orochi includes the following sections:
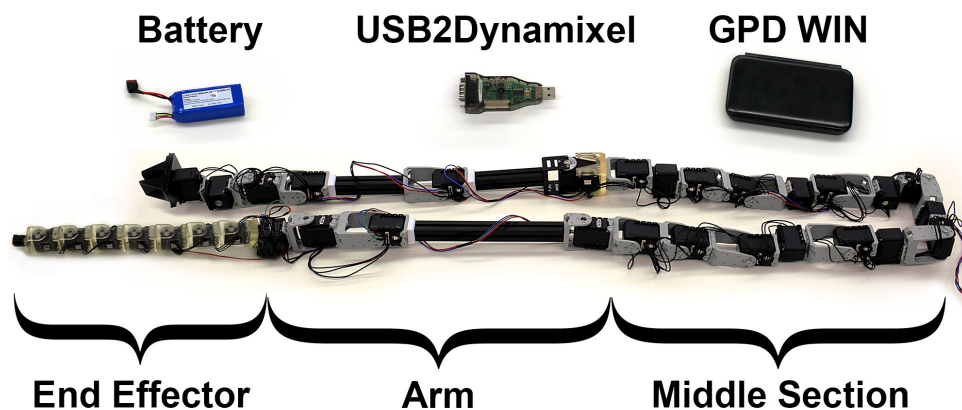
Figure 11 Orochi with 25 DoF. The length can be adjusted by adding or removing servos in the middle section.

1- *Middle section:* This section is customizable with a variable number of AX-12A servomotors, making Orochi flexible so it may be worn on the wearer's neck, waist, arm, or leg fulfilling the design consideration of *wearability by context*.

2- *Arm sections:* Both arms have four AX-12A servos, and the right arm includes a stronger MX-64AT servo connecting it to the middle section for better handling slightly heavier objects. The arms can lift objects weighing only a few hundred grams, but they can statically hold objects of up to one kilogram. The links on each arm were extended using extruded aluminum profiles and 3D-printed adapters to maximize the reachable workspace and reduce weight, compared to having a

longer chain of servos. On the one hand, weight reduction enables manipulating heavier objects, while on the other hand, extended links between the servos reduce the robot's wrapping capabilities.
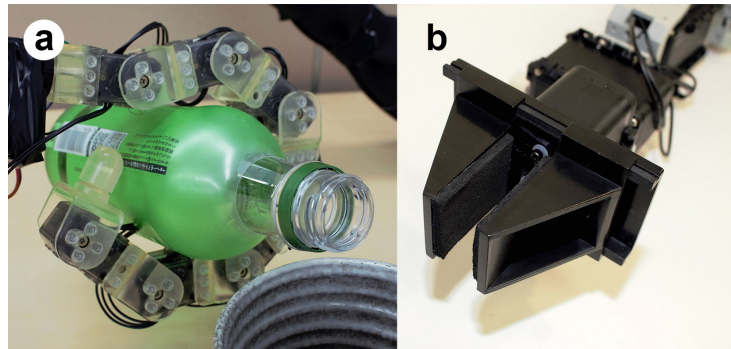
Figure 12 a) Tentacle holding a bottle and b) parallel gripper.

3- *End effectors:* End effectors can be attached to both arms, and Orochi was tested with two types. A parallel gripper, using an AX-12A servomotor, was installed at the end of the stronger, right arm of the robot (Figure 12b), enabling simple physical interactions, such as grasping, pushing, or pulling objects. On the left arm, a tentacle of seven XL-320 servomotors was installed. The high DOF of the tentacle enables flexible wrapping and delicate manipulation of objects (Figure 12a). For example, it can press buttons, grasp bottles, and perform other tasks requiring high dexterity. The combination of two types of end effectors enables multiple methods of interaction with surrounding objects, satisfying the design consideration *multipurpose use*.

4.2.4.1 Actuation and Mechanical Design

The rated stall torques of the Robotis Dynamixel servomotors XL-320, AX-12A, and MX-64AT are 0.39 Nm, 1.5 Nm, and 5.5 Nm, respectively, but stable motions are possible only with loads of up to approximately 20% of the stall torques, according to the manufacturer (Robotis 2019). We chose these motors because of ease of mechanical connection in different configurations and the available software libraries for control. Previous approaches, such as (Llorens-Bonilla, Parietti et al. 2012, Parietti and Asada 2016), placed the motors as close to the body as possible and used tendons or timing belts to actuate joints further from the body. This design choice minimized the weight of the robot arm, thereby maximizing its lifting capacity. We chose to distribute the motors over the whole of Orochi to avoid underactuation and to maximize the number of poses in which it can comfortably be worn and used. For the same reason, we also chose not to have a fixed base. Our actuation design is similar to those of (Leigh and Maes 2016, Saraiji, Sasaki et al. 2018), which also enable multipurpose use.

4.2.4.2 Control Unit and Power

We use a small Windows 10 PC (GPD WIN (GPD 2019) to run the control software. The PC is connected to the robot via a USB2Dynamixel serial adapter (Figure 11). The servomotors are daisy-chained on a TTL-level multidrop, half-duplex, asynchronous serial communication bus. Orochi is powered by an 11.1 V, 3500 mAh, lithium polymer battery, which can power the robot for approximately 20 minutes of active use. Orochi can also be connected to an external power supply.

4.2.4.3 Control Software

The complexity of robot control inspired us to develop Orochi controls as a platform for exploring actuated wearables from an interaction perspective. The main design objective

of our software is to enable rapid prototyping and implementation of various I/Os, control methods, and robot morphologies. Therefore, our system is developed to enable maximum flexibility for prototyping, which can serve as a testbed for a variety of case studies. Accordingly, building a completely autonomous wearable robot is out of scope of our work. However, the current implementation can be extended to allow Orochi, or subsequent robots, to be autonomous by integrating intelligent motion planning, controls, and input from multiple sensors.

Our toolkit is implemented using C# and the overall structure of our software is shown in Figure 13. In order to reflect the design objectives discussed before, we constructed our control software based on five layers:

1- **Hardware Controller Layer**: which comprises low level communication and control code for manipulating the servomotors using the TTL protocol as specified by Robotis (Robotis 2019). This layer can be extended to support other servomotor or actuator types from other manufacturers.

2- **Abstraction Layer:** We implemented and abstracted manufacturer-specific robot communication, control, and feedback, so they are fully invokable through a unified servo-class interface. This structure allows us to treat each servomotor as a class with various attributes and methods. Robots are thereby constructed by adding a series of servos in doubly linked list or an array, where the robot can comprise a variety of servomotor types in different configurations. The abstraction allows us to rapidly experiment with different configurations and morphologies without altering our code.

3- **Basic Control Layer:** We implemented a variety higher-level control attribute. For example, the ability to save, load motions and sequences of motions. To create a routine, the user physically moves the joints to the desired location and saves it as a motion. By combining multiple motions, sequences can be created and played back with varied attributes (e.g., speeds and torque limits). We also implemented a basic motor compliance mode.

4- **Interface Layer:** this layer is mainly created for accessing and controlling the robot in various methods. We implemented three main methods to control the robot. First, we created a *graphical user interface* (GUI) to enable creating, saving and loading motions and sequences. Secondly, we created a *network interface*, using Websockets (Websocket.org 2019), to enabling controlling the robot. All abstracted robot controls can be accessed through a network, which facilitates experimenting with different control and feedback methods, motion planning systems, and input or output devices. The network interface also includes a graphical user interface module to allow basic server control and debugging. Lastly, we created a module to *embed a number of manual control methods*, such as using buttons, which are used to trigger various motions or sequences.

5- **External Modules:** the external modules comprise a variety of control and interaction modules that serve specific functionalities. In our code, we implemented four essential ones. The first module is an inverse kinematic solver that allows calculating the end-effector position with respect to various attributes. This is essential for various physical manipulations. The second module is the sensors unit, where we integrated a camera module that was used for AR control (more in section 4.4). Cross-device interactions with digital appendages was also implemented by integrating digital devices/services over the network, enabling various shape-changing and haptic experiences (more in section 5.3.3 Digital Interaction Design). Finally, we integrated a variety of input methods over

the network, such as smartphone controls (as shown in Figure 15).

External Modules

Inverse/Forward Kinematics Solvers | Sensor Units | Digital Services/Devices | Input Methods (Joysticks..etc)

Websockets

Interface

Graphical User Interface Controls | Network Interface | Input, output methods and sensors

Basic Control

Motor Compliance Mode | Motion and Sequence Generator/Player

Abstraction

Basic Servo I/O Module

Hardware Controller

Robotis Motor Controller Library (XL320, AX12A, MX64AT)

Figure 13 This figure illustrates the overall control system implemented to control Orochi as well as all other robots. It consists of five main layers, and is constructed with the purpose of rapid prototyping and experimentation for a variety of input and output modalities and control schemes.

4.2.5 Exploring Novel Interactions Using Orochi

Compared to surveyed SRLs, Orochi's malleable body and different end effectors enable a variety of novel interactions. In this section, we explore some of these use cases. Orochi can seamlessly augment users; it can be used to interact with objects in front of, behind, or below the user (Figure 9Figure 9a, Figure 14a). Orochi can also extend the reach of the user's arm, enabling them to interact with objects at a distance (Figure 14b). Orochi can augment users' manual capabilities. For example, it can act as an extra finger to assist in holding large objects in one hand or grasping multiple objects (Figure 14c, d).
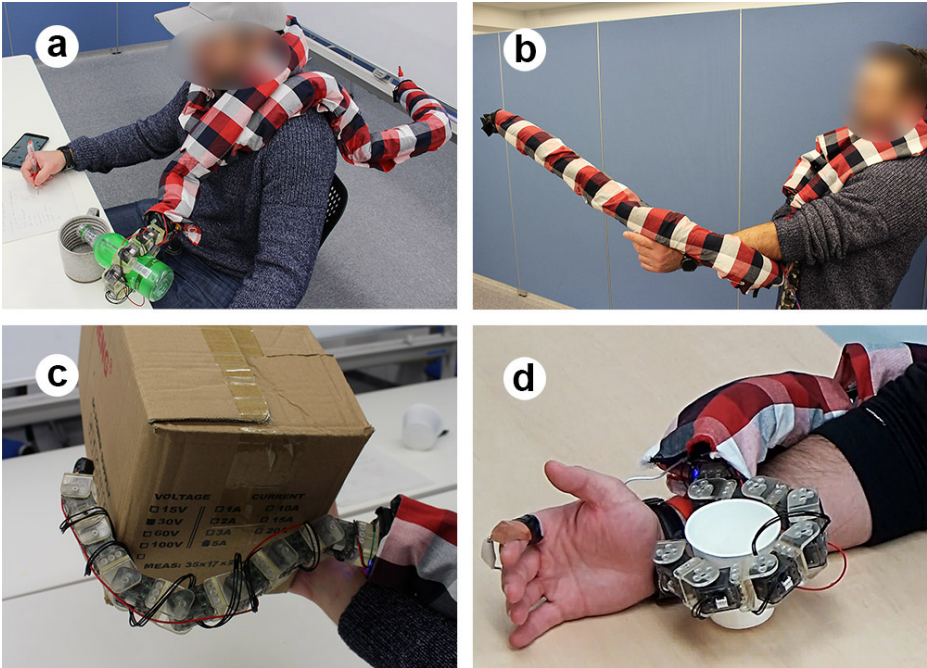
Figure 14 Orochi can seamlessly augment the user with a) an extra arm in front of or behind the user, b) extend hands reach, or augment them with extra fingers to c) grasp large objects or d) to hold more objects.

Manipulating physical objects is a fundamental capability of SRLs, and Orochi can manipulate a variety of objects. For example, it could retrieve an object upon the user's request. We developed a remote-control application and deployed it on an Android smartphone, which connects to the control system using WebSockets. The application allows users to manually control Orochi's arms and end effectors to manipulate objects (Figure 15), when it is worn or detached.
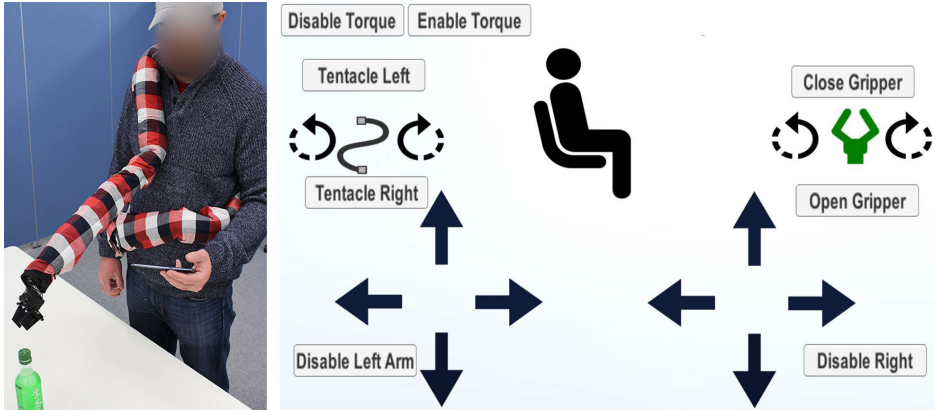
Figure 15 Controlling Orochi using a smartphone. (Right) A snapshot of the smartphone application showing controls for the left and right arms, end effectors, disabling or enabling torque in different sections, and for triggering motions and sequences.

Orochi's flexibility also enables novel types of haptic feedback. As Orochi can be worn differently by context, it can deliver these haptic cues virtually anywhere around the user's body. Both novel haptic cues and their delivery on various areas around the body provide intriguing interaction possibilities beyond what has previously been explored. These include, for example, tapping, gestures, pinching, or pulling users' clothes (Figure 16a,b) .

Figure 16 a,b) Orochi can deliver a haptic feedback in different locations and c,d) augment interactions with digital devices, such as a smartphone, in different ways.

Orochi can augment interactions with digital devices. For example, with a smartphone (Figure 16c), Orochi can actuate the screen in response to events (e.g. applications, notifications) or to provide dynamic affordances. Orochi's body can also complement feedback from a smartphone, such as by pointing to where a user should be heading when using a navigation application. Orochi can also be used to operate digital devices (Figure 16d).

4.2.6   Evaluation 1: Daily Usage Focus Groups

Objectives and Participants: We wanted to explore how users would perceive our intended design factors embodied in Orochi, and how they would use Orochi in their daily lives. Therefore, we conducted four focus groups involving 21 participants. The participants came from ten countries and diverse backgrounds (finance, business, engineering), were aged between 22-34 years (m=25.57, 4 females), and indicated they knew about SRLs from research or sci-fi media. We chose focus groups because they are robust and flexible enough to capture user-centric qualitative information, such as usability expectations or challenges (Rosenbaum, Cockton et al. 2002, Kim, Kwak et al. 2009).

Procedure: We conducted each focus group in two phases. *Phase one* used unguided brainstorming so that we could learn how Orochi may be used and worn in unrestricted contexts proposed by the participants. In *phase two*, we restricted the session to the specific contexts of 1) working while seated at a desk, which included a setup of a simple working environment with stationery and a PC, and 2) daily commuting. We chose these two scenarios because they have different contextual factors, such as tasks and locations that can affect Orochi's usability.

Flow: After collecting demographic data, we started *phase one* by briefly introducing Orochi. We explained that Orochi's length and end effectors were changeable and did not specify wearability methods or usage contexts. Next, participants were handed Orochi, and each was given time to inspect and wear the device without instructions. Then they were given 20 minutes to discuss and brainstorm use cases. *Phase two* was conducted similarly to phase one, yet with a focus on specific interaction contexts. We concluded with a usability questionnaire (5-point Likert scale, 5 represents strongly agree) and semi-structured interviews.

4.2.7 Results and Analysis

4.2.7.1 Use Case Analysis
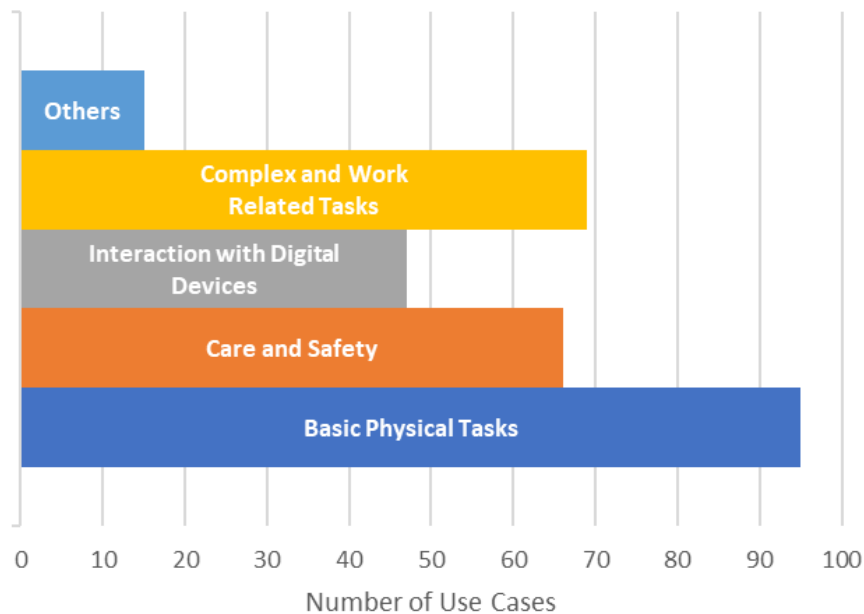
Figure 17 Use case distributions

We build upon our previous work (AlSada, Khamis et al. 2017) and extended the categories in activities of daily living (Katz, Downs et al. 1970) to classify **292** collected use cases as the following: *Basic physical tasks*, such as pushing, pulling, carrying, and holding objects included **95** use cases. In such scenarios, Orochi is advantageous for reaching objects at a distance, for handling hot or cold objects, and for holding heavy objects for extended periods of time. *Complex and Work-related Tasks* (**69** use cases) included interactions such as assisting with house chores and operating professional tools and factory machinery. *Care and safety* (**66** use cases) included activities, such as personal hygiene, feeding the user or preventing them from falling when losing balance. Next, *Interaction with Digital Devices* (**47** use cases) included tasks such as swiping a touch-screen or typing on a keyboard. Most cases emphasized interactions with a smartphone while walking, where Orochi is used to take selfies or answer the phone automatically. *Other tasks* (**15** use cases) included supporting people with disabilities, use as a companion robot, and waving greetings to other people.

Participants demonstrated several intriguing scenarios that were not considered in our initial designs. For example, transforming and using Orochi as a chair, an exoskeleton to strengthen their arms or legs, or as a companion robot with which users can chat and interact. Moreover, participants expressed scenarios in which they would not want to use Orochi due to social acceptability or trust concerns, such as for shaking hands or for delicate tasks like applying eye ointment. Lastly, the scenarios excluded haptic and shape-changing experiences. We believe participants were not acquainted with such topics; therefore, future focus groups should involve experts in those domains.

Overall, the breadth and diversity of collected use cases indicate that participants perceived Orochi as a multipurpose wearable for daily use. This was further asserted in the interviews, where participants described the potential of using Orochi in a variety of contexts and scenarios. One participant said, *"I like the possibility of doing anything I want with it."* Another added, *"It can be used in many ways; you just need to adapt it to what you want to do. It's all up to your imagination."* Thus, we believe the design consideration *multipurpose*

use was well received. We discuss the results implications, opportunities, and challenges within the next section.

4.2.7.2   Wearability by Context

During the focus groups, participants showed individual wearability preferences of Orochi in different contexts, thereby satisfying the design factor *wearability by context* (Figure 18). Yet, as our current robot must be manually wrapped to be worn in different postures, it was physically and mentally demanding to fit the robot in each posture. Therefore, future work should focus on automating wearability to ease affixing the robot, and to provide the user with guidance regarding the most convenient way to wear Orochi in different interaction context.

Figure 18 a) One participant preferred wearing Orochi as a scarf that automatically covers his face when it is cold. b) One participant placed it in a backpack, and another c) around his seat, doubling as back support and to retrieve objects.

4.2.7.3   Comfort and Fit

Opinions about Orochi's comfort varied (*m=3.1, SD=0.87*). Participants thought the weight should be reduced, especially as prolonged wear around the shoulders tired some users. They also highlighted the bulkiness of the mechanical components as they can be conspicuous and uncomfortable. They thought higher degrees of freedom would be required for better wrapping. We conclude that the weight must be reduced and the flexibility in the middle section increased.

4.2.8   Evaluation 2: Unobtrusiveness Survey

Objective: Although Orochi was designed to be publicly unobtrusive, how users wear or use Orochi may draw different levels of undesired attention (Dobbelstein, Hock et al. 2015, Profita 2016). Surveys have been shown to be effective for studying social acceptance of emerging systems (Koelle, Kranz et al. 2015, Alallah, Neshati et al. 2018), therefore, we designed a survey to investigate how noticeable Orochi would be when worn in public.

Participants: We hired 40 participants, coming from 15 countries, varied backgrounds, aged between 19-67 (*m*=28.12, 8 females).

Procedure: The survey depicts participants as spectators (Koelle, Kranz et al. 2015); they were asked about their opinions when they saw others wearing and using Orochi in 5 public contexts. The survey consisted of 5 sections, each section started by showing and describing one context from Figure 19, followed by questions to rate Orochi's noticeability (6-point Likert scale, 1 is unnoticeable) and to gauge Orochi's obtrusive aspects within that context. After finishing all the sections, we concluded the survey by gathering overall impressions of the public use of Orochi. We counterbalanced the survey by reversing the order of the sections for 20 participants.

4.2.8.1   Unobtrusiveness Survey Results

Initial results from the focus group participants were generally in favor of wearing Orochi publicly (*m*=3.7, *SD*=1.64). One participant said: *"You can walk without people noticing you are wearing a big robot on your neck."*. The survey results revealed further insights about usability, wearability and unobtrusiveness within various contexts of daily use. In this section, these results and presented and analyzed, after which their design implications are discussed.

Survey results reveal additional insights about Orochi's use in public. Participants allocated different ratings to indicate how noticeable Orochi was during public interactions, where more noticeability means drawing undesired attention when worn publicly in current societies. Figure 19 When Orochi was retracted, it was not very noticeable. Therefore, it is mainly perceived as a garment. However, Orochi draws more attention when in use (Figure 19). For example, when Orochi is holding multiple objects (c,e), when physically interacting with objects (d). Although Orochi's is designed to be unobtrusive as possible, its usability raises a number of concerns and continually draw undesired attention.

To analyze the ranking, we ran non-parametric Friedman test, which showed significant differences in the distribution of the experience's ranks (χ^2 (4)= 79.245, p<0.001). We followed with Wilcoxon signed ranks test with Bonferroni correction, which only revealed significant difference

	a	b	c	d	e
m	1.90	2.57	2.95	3.88	4.43
SD	1.03	1.43	1.38	1.44	1.30

Figure 19 Orochi's noticeability ratings in each context, The low ratings in (a,b) show that Orochi is mostly unnoticeable when retracted, and more noticeable when used (c,d,e).

Condition	a-b	a-c	a-d	a-e	b-c	b-d	b-e	c-d	c-e	d-e
Z	-2.913b	-3.550b	-5.023b	-5.191b	-1.006b	-4.521b	-5.102b	-3.514b	-4.105b	-2.552b
P value	0.003581	0.000385	5.08E-07	2.09E-07	0.314644	6.15E-06	3.36E-07	0.000442	4.05E-05	0.010709

Table 1 this table shows statistical analysis results among the various evaluation conditions.
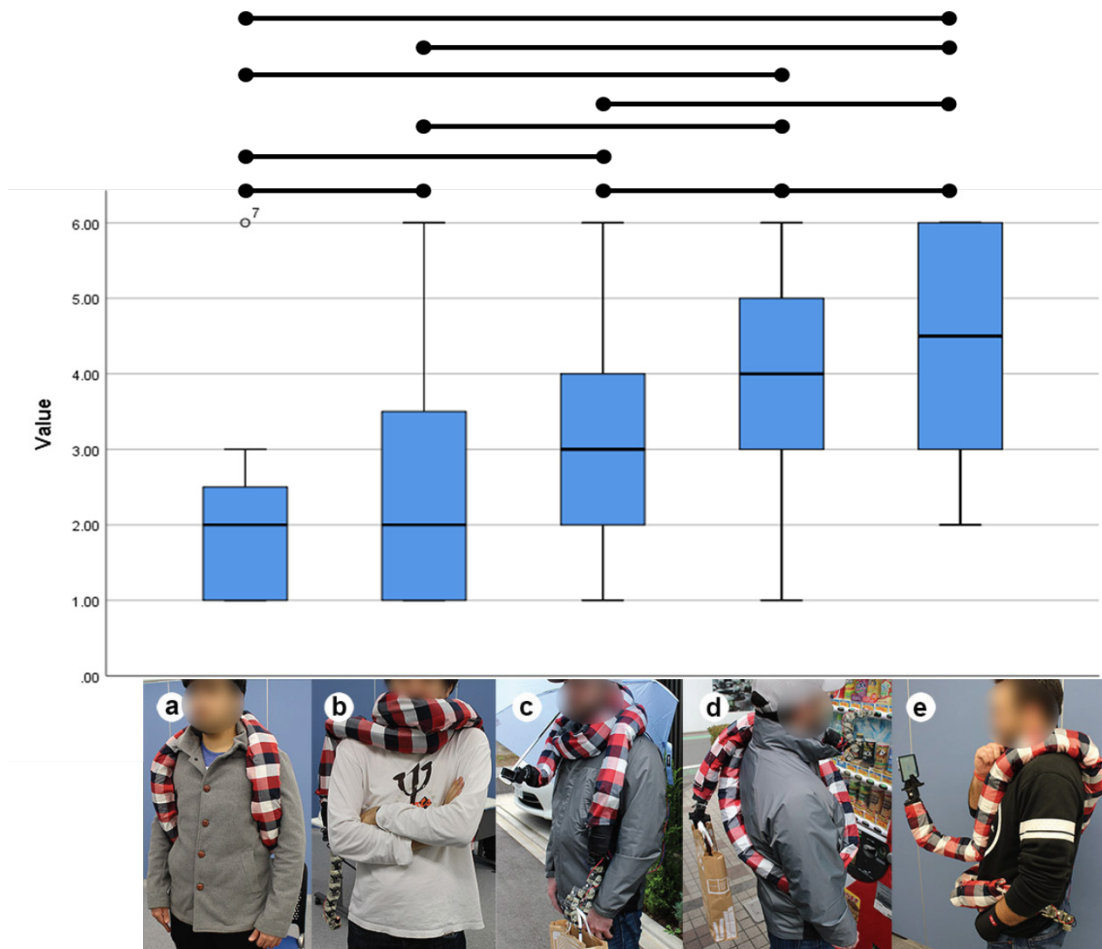
Figure 20 Significant effects are observed between most of the cases, therefore indicating that Orochi was perceive as a garment when folded (i.e. case a and b), while it was more noticeable when in use.

We asked participants to rank the various factors that effected their judgement when rating Orochi's obtrusiveness. Accordingly, these results are reported in Figure 21. In order to analyze the assigned ranks, we ran nonparametric Friedman test, which showed significant differences among ranks (χ^2 (6)= 26.786, p<0.001). We followed with Wilcoxon test to identify the differences among the ranks, applying the Bonferroni correction. However, a significant difference was found among length-thickness (p < 0.005) and length-end effectors (p < 0.005). The rest of the ranks did not show any significant differences.

Participants emphasized Orochi's revealed end-effectors, novel shape and interactions as main contributing factors to its noticeability. We conclude that our approach successfully maintains Orochi's unobtrusiveness when retracted, yet social acceptance during active use of Orochi depends on several factors, such as how commonly this form of wearable is used, which require much deeper investigations.
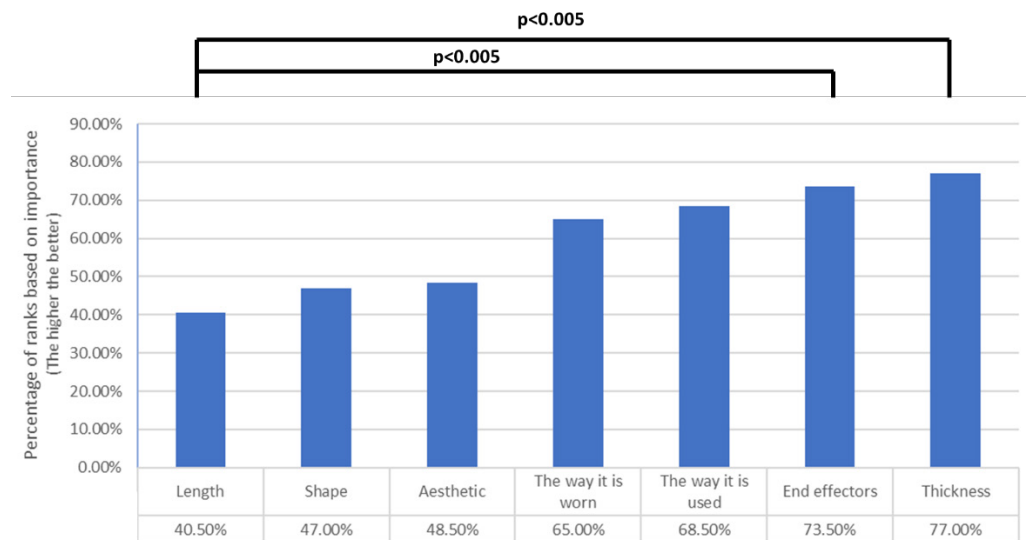
Figure 21 Analysis of various factors that effected Orochi. The higher the rank, the more essential the factor has to be addressed to improve Orochi unobtrusiveness.

4.2.9 Discussion and Future Work

Overall, our realization of the design considerations in Orochi was well received by the focus group participants. Participants demonstrated a variety of usage scenarios, wearability preferences, and were in favor of wearing Orochi in public. We demonstrated Orochi's multipurpose capabilities by implementing applications with physical manipulation, haptic feedback, and shape-change within daily usage scenarios. Our work reveals several opportunities for future work and research in this area. We discuss some insights extracted from implementing Orochi, focus group results, and developed applications.

Multipurpose Use: Orochi can perform several tasks in addition to those specified in the multipurpose design consideration or mentioned in the use case analysis. We identify the following: Self-expression and hedonic uses, such as using it as a tail or to actuate clothes. These can be implemented using the tentacle or gripper. By passing the control of Orochi to other users, novel experiences, such as teleoperation, telepresence, and affective haptics, can be delivered. This can be achieved both when Orochi is worn and detached (Figure 1a). Therefore, evaluating the hardware capabilities within various interaction contexts, beyond initially intended domains, would be valuable.
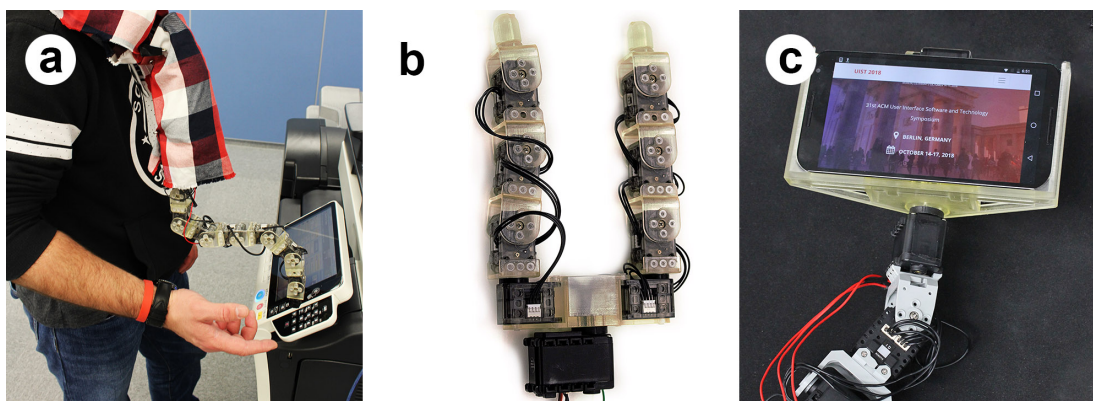
Figure 1. a) A teleoperator could aid the wearer in tasks requiring multiple hands, or tasks requiring instruction or assistance from the teleoperator. b) Double tentacle end effector. c) Phone holder end effector.

Designing serpentine-shaped robotic appendages as Tools or Social Companions? Our analysis of use cases indicates two expectations of the roles Orochi is expected to fulfill: An augmentation tool or a companion wearable robot. These two roles indicate two different interaction paradigms: *1) Explicit interactions (Schmidt 2000)*: Orochi is generally perceived as a tool for extending users' physical interaction capabilities (Leigh, Denton et al. 2018), such as extending the users reach or enabling them to carry large objects in one hand. In this case, Orochi is reactive to and reflective of the users' explicit intent. *2) Implicit interactions (Schmidt 2000)*: Orochi is expected to be highly independent from the user, exhibiting high autonomy and intelligence. Participants associate this mode with Orochi being a companion or embodied agent, where it possesses anthropomorphic traits, like conversational robots (Kashiwabara, Osawa et al. 2012), and can take the initiative to execute tasks proactively without user initiation or with minimal intervention.

Each role that Orochi plays has implications for interaction, control, and mechanical design. As an augmentative wearable robot, explicit interactions through lower-autonomy controls could be sufficient (Endsley and Kaber 1999, Leigh, Agrawal et al. 2018) for example, using EMG-synergetic controls (Hussain, Spagnoletti et al. 2016, Leigh and Maes 2016) or passing control to the user's limbs (e.g. leg (Saraiji, Sasaki et al. 2018)). As a companion or embodied agent, implicit interactions with higher autonomy (Beer, Fisk et al. 2014, Ojuroye, Torah et al. 2016) and anthropomorphic interactions (Fink 2012) are essential, such as with high-level dialog and using human-like cues (e.g. facial expressions and gaze). Therefore, such wearables require intelligent controls, motion planning, and high context awareness of surroundings, user intent, and task objectives, which should be matched with suitable sensors, I/O methods and intelligent control systems. An important future research direction is how to design a cohesive user experience that interweaves multiple robot roles, as well as digital interactions, such as haptic and shape-changing experiences. How should the experience smoothly transition between each role in different contexts?

Social acceptability: As with other emerging technologies, publicly using wearables like Orochi raises unexpected social or adoption issues that we should further investigate. Although we highlighted insights related to Orochi's undesirable use cases and unobtrusiveness during use, there is a dearth of studies on using SRLs in public. An important research direction is to study the social implications using in-the-wild field studies.

Will multipurpose wearable robotic appendages replace smart devices, or will serpentine-shaped robotic appendages interact with them? serpentine-shaped robotic appendages can be augmented with features to replace other devices, such as mobile phones. It remains unclear which path multipurpose SRLs will take: Will users prefer SRLs that allow them to interact with digital devices, similarly to how Orochi is used in Figure 16 d, or will they prefer to have extra functionalities built into an SRL? For example, the SRL could include a screen that provides access to multimedia. Orochi is well positioned to evaluate both directions. A future study could investigate whether users prefer to use digital devices via Orochi or have such functionalities integrated in Orochi.

Optimizing Orochi: As Orochi was designed for maximum wrapping flexibility, its handling capacity was thereby reduced, resulting in a slightly underpowered robot. Upgrading Orochi with stronger and larger motors would have weight and bulkiness trade-offs. We will optimize Orochi's design based on our gathered use cases. Moreover, we will investigate soft robotics and tendon-driven structures, which have the potential to reduce Orochi's bulkiness, while providing high actuation power.

Safety: Our wearability method depends on pressing the robot against the user's body for stabilization during use. This poses safety risks, especially in sensitive regions of the body. When in use, the arms could collide with the user's body and cause injury. New methods are

necessary for detecting the user's posture and limb locations to avoid collisions. Since previous work has studied robot safety within other domains (Veneman 2017), future research should analyze and identify potential risks and investigate safety mechanisms that are suitable for daily used appendages.

4.2.10 Conclusion and Summary

This project presented and evaluated Orochi, a multipurpose daily worn SRL, designed based on three design considerations: multipurpose use, wearability by context, and unobtrusiveness in public use. We provided our vision of how each of the design considerations could be embodied, followed by an implementation and an evaluation of our design concepts. We explored several intriguing applications of Orochi, which further emphasized its multipurpose capabilities. We also carried out two evaluations that focused on validating our design considerations. The results validated our design and provided evidence that Orochi's design matches our established daily interaction and wearability needs.

Orochi presents the first steps to realizing our vision of future daily worn serpentine-shaped robotic appendages for everyday use. However, there exist a number research challenges in interaction design and controllability of the robot across the daily context. The evaluation results also provide numerous insights that contribute to addressing the research questions, which are specifically discussed within Chapter 5.

The flexibility of Orochi's form factor provide a wide variety of interaction possibilities, such as cross-device interaction with smart devices or within internet of things applications. Additionally, one of the main challenges of serpentine-shaped robotic appendages is the design of multipurpose user experience. Orochi's evaluation provides the essential insights regarding the various interaction expectations and paradigms, which reflect implicitness and explicitness that are both required within daily interaction contexts. Therefore, these insights are further investigated within the design, development and evaluation of weARable in section 4.4.

4.3 HapticSerpent

4.3.1 Introduction

Haptic feedback has long been investigated as a method to increase the immersion or enhance the interaction within virtual reality (VR). Many modern VR platforms, like HTC Vive and Oculus Rift, allow players to move around physically in a tracked space while being engaged in VR. Accordingly, numerous consumer products and research literature investigated wearable haptic feedback methods for areas like the arms, hands and torso. Yet, other body areas, like the neck, face, head or others, have largely been unexplored for their validity for haptic or tactile feedback, especially within the context of VR.

Figure 22 the idea of HapticSerpent is to investigate novel haptic feedback in VR. For example, within a VR experience, if the user is punched by the VR character (Left) the robot can simultaneously deliver feedback with matching physical properties (Right), such as strength, speed, angle of contact or location.

While there exists a large body of works around vests for vibrotactile feedback around the torso (Kaspar, Konig et al. 2014, Morrison, Manresa-Yee et al. 2015) , such works remain limited in terms of the diversity of haptic or tactile feedback as well as their capability to deliver feedback to other locations on the body. Therefore, we developed HapticSerpent, which is a waist-mounted six degrees of freedom (DOF) serpentine robot arm that is capable of providing various haptic experiences (Figure 23). HapticSerpent represents a specific use case of serpentine-shaped robotic appendages, where its worn location and form factor is fixed, and its interaction domain is focused on leveraging its capability to deliver haptic feedback.

The objective of this use case is to explore novel haptic feedbacks enabled by serpentine-shaped robotic appendages, and understand the user acceptability of receiving various forms of haptic feedback. Although novel haptic feedback has a direct and feasible application within VR systems, the evaluations carried out in this use case are generalizable to other applicable domains.

In contrary to previous literature and existing commercial products, HapticSerpent can provide a variety of haptic feedback types, such as producing normal or shear forces, as well as gestural output (Roudaut, Rau et al. 2013, Schneegass and Voit 2016), such as poking or stretching the skin. Second, HapticSerpent is capable of haptic feedback in multiple locations on the body (Figure 23). In this chapter, the prototype specifications is presented, followed by an investigation of possible of intriguing feedback methods enabled by the HapticSerpent. Moreover, to evaluate the acceptability of receiving haptic feedback in VR, we carry out two surveys. The first focuses on the general acceptability of receiving haptic feedback in different body locations. The second survey focuses on the acceptability of specific feedback types delivered by HapticSerpent. Accordingly, the results of these surveys are presented and analyzed. Lastly, the chapter ends with a discussion of the advantages of our design direction within the context of haptic feedback, highlighting various challenges and opportunities for future work.

The main contributions of this case study are as follows: 1) The design and implementation of a wearable haptic/tactile feedback robot that is capable of a variety of feedback methods in multiple locations on the body. 2) Exploration and presentation of novel haptic feedback capabilities within VR. 3) Preliminary evaluation results that gauged general acceptability of receiving feedback from HapticSerpent on different areas of the body.

4.3.2   Haptic Feedback in Commercial and Research Domains

Previous works have investigated a variety of feedback methods that can enhance VR experiences. Several works explored vibrotactile feedback at various locations on the body, especially the chest (Jones, Nakamura et al. 2004, Konishi, Hanamitsu et al. 2016). Other works attempted to simulate impacts and pressure using solenoids a vest (Tactile-Gaming-Vest 2010). Yet, such feedback remains confined to predetermined points and is limited to a single type. Likewise, various commercial products like Hardlight VR (Hardlight-VR-Suit 2019) and Eyeronman (Tactile-Navigation-Tools 2019) are vests that embed vibrotactile motors for feedback similar to previously mentioned literature. Thus, we conclude that surveyed literatures and products were mainly confined to delivering feedback to fixed stimulation points (as in (Konishi, Hanamitsu et al. 2016)) and were mostly capable of vibrotactile feedback.

4.3.3   The Design of HapticSerpent
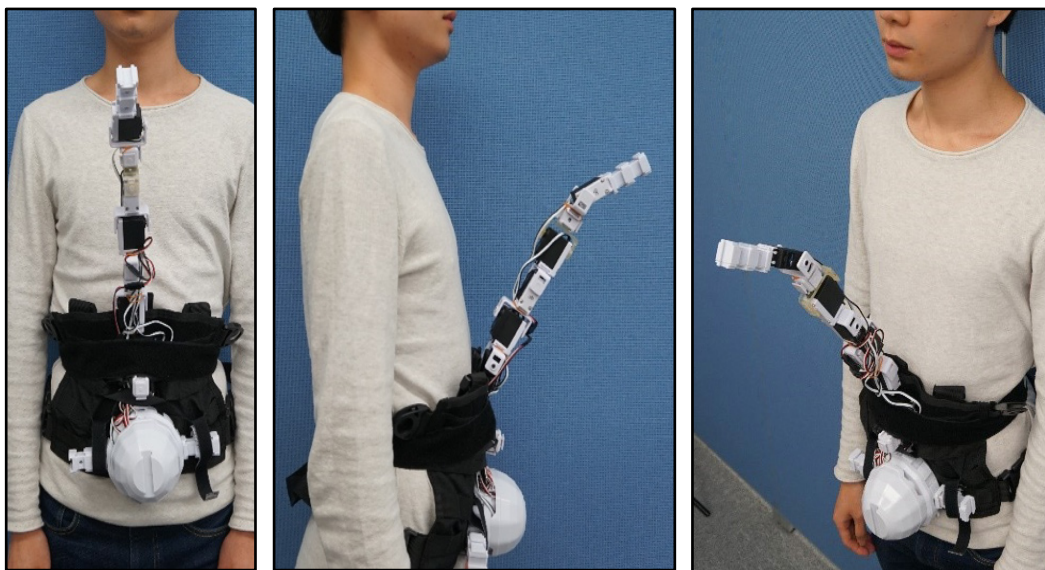
Figure 23 Front, side and oblique views of the HapticSerpent

Design Objective: The objective of the HapticSerpent is to be able to deliver taps and gestures in different locations and force magnitudes with the lightest possible weight. The robot can be worn in the front or back torso.

Robot Design: The robot's body comprises six serially connected hobby servomotors as shown in Figure 1 (EZ Robot (EZ-Robot.com 2019)), Stall torque = 1.9 Nm). The servomotors are linked together using plastic brackets, which are light in weight and their formation can be reconfigured to match different body dimensions.

Robot Dimensions and Attachment: The robot weighs 742 g and its total length is 51 cm, both robots are mounted on a base with extended brackets and attached to a multitool vest (Figure 1), weighing 300 g. The vest enables easy wearability, adjustment and fit for a variety of users.

End-Effector: We used a 3D-printed bracket (W=3 cm, H=3 cm, L=6.5 cm) and attached it to the last servo to be used as an end-effector. We chose this end-effector size as it is slightly bigger than a human-finger, which provides a bigger contact surface when applying taps. Also, this end-effector is long enough to enable adjusting its direction when delivering feedback. Other End-effectors with varied dimensions or shapes can also be used, such as softer or sharper end-effectors.

Control and Power: To control the robot, we utilized an EZ-Robot Control-Board (EZ-Robot.com 2019). We designed network-invokable controls on top of the EZ-Builder framework to enable easy creation and playback of movements. We powered the robot using 8 v 1800 mA Li-Po battery (approx. 25 minutes of continuous use).

Figure 24 the mechanical design of HapticSerpent. The robot consists of six serially connected servomotors with a fixed base. The dome-shaped structured houses the microcontroller units and Li-Po battery, which are in turn controlled through WI-FI.

4.3.4 Exploring Novel Feedback with HapticSerpent

Although the main design direction of the HapticSerpent is to delivering taps and gesture-based feedback, its unique formfactor allows for a variety of feedback types. We explore a variety of these feedbacks within this section.

Using the robot end effector, HapticSerpent can apply various types of normal and shear forces with varied durations and magnitudes. Furthermore, by varying and combining forces, HapticSerpent can provide a variety of feedback, such as pushing, pulling, hitting, scratching and pinching (Figure 25). Gestural feedback (Roudaut, Rau et al. 2013) can also be created by applying directional and tangential forces on the user's body (Figure 25 and Figure 26). Moreover, the flexibility of the robot allows it to deliver feedback to a variety of locations around the body (Figure 26). Such locations and feedback types are unexplored within related literatures.
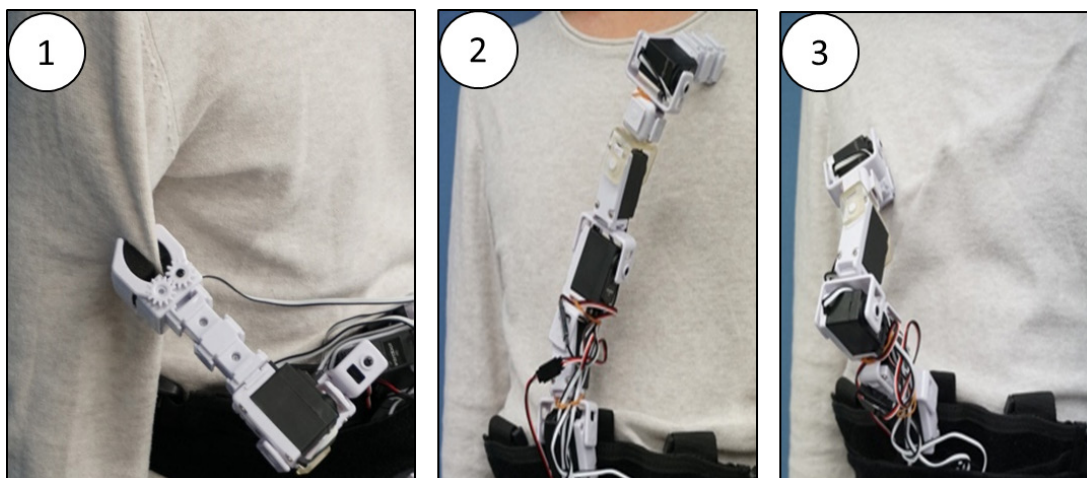
Figure 25 (1) Pinching and pulling the user's clothes. (2-3) HapticSerpent scratching the user's chest diagonally. Such types of feedback can be applied with varied magnitudes, directions and speeds.
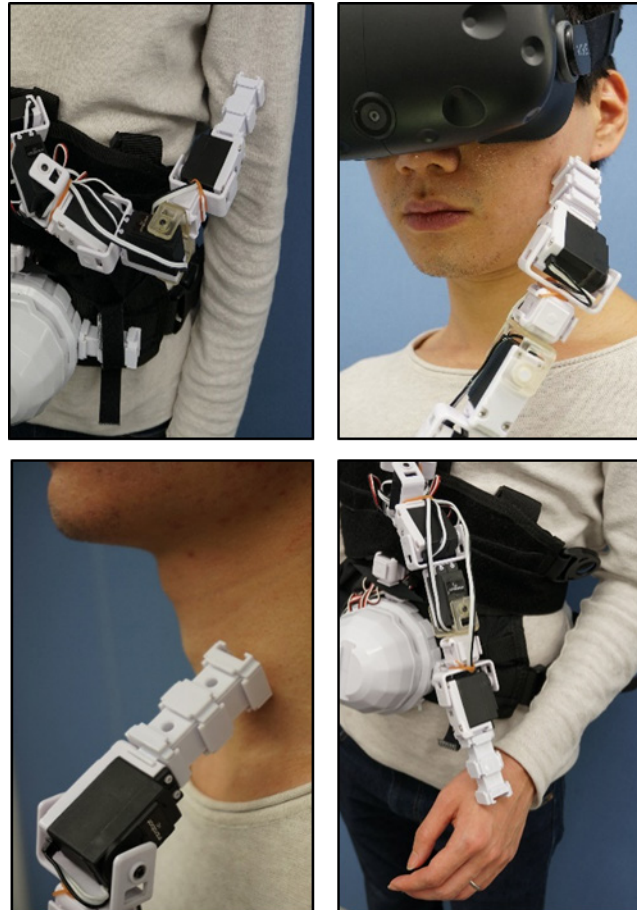
Figure 26 : Different types of feedback could be applied to various body locations, which shows the versatility of HapticSerpent as a multifunctional haptic feedback robot.

4.3.5 Survey of General Acceptability of Haptic Feedback on the Body

Objective: Receiving haptic feedback around the body is an intriguing aspect of the HapticSerpent. However, the acceptability of receiving haptic feedback is generally not known. For example, users may prefer to receive haptic feedback on specific areas, while other areas could be generally unacceptable to receive feedback at. Therefore, it is important to understand the general acceptability of receiving haptic feedback in various areas around the body. Such knowledge can be used as basis to design haptic feedback for a variety of experiences, such as for notification delivery, for embodying digital objects in AR or to increase immersion in VR. Therefore, we surveyed a total of 28 (23 males) college students, who came from various backgrounds, and who had prior knowledge about wearable robots and VR from sci-fi media.

Procedure: We created a survey based on a 5-point Likert scale (1 is Totally Unacceptable, 5 is Totally Acceptable). Each question gauged a specific area on the body as shown in Figure 27. Prior to answering, the participants were briefed about HapticSerpent and its feedback capabilities. The type of haptic feedbacks was also explained, where we e explained that haptic feedback comprised taps, gestures and pinching and pulling clothes (using the gripper). Then, a series of questions requested the participants to rate the acceptability of receiving haptic feedback on different body regions in general (without limiting them to specific context). Finally, the results were collected and analyzed.

Results: As shown in Figure 27, Participants voted highest acceptability for the torso, arm, hand, legs and back areas, and they gave medium scores for the feet and butt areas.

Participants were generally skeptical about receiving feedback on delicate areas like the head or waist, yet some thought it could be acceptable. 39% of participants scored 3 or above for feedback on the *head*, 20% for the *face*, 29% for the *neck*, and 18% for the *waist* areas. Participants also elaborated that feedback like tickling on the cheeks or gentle face taps would be tolerable.
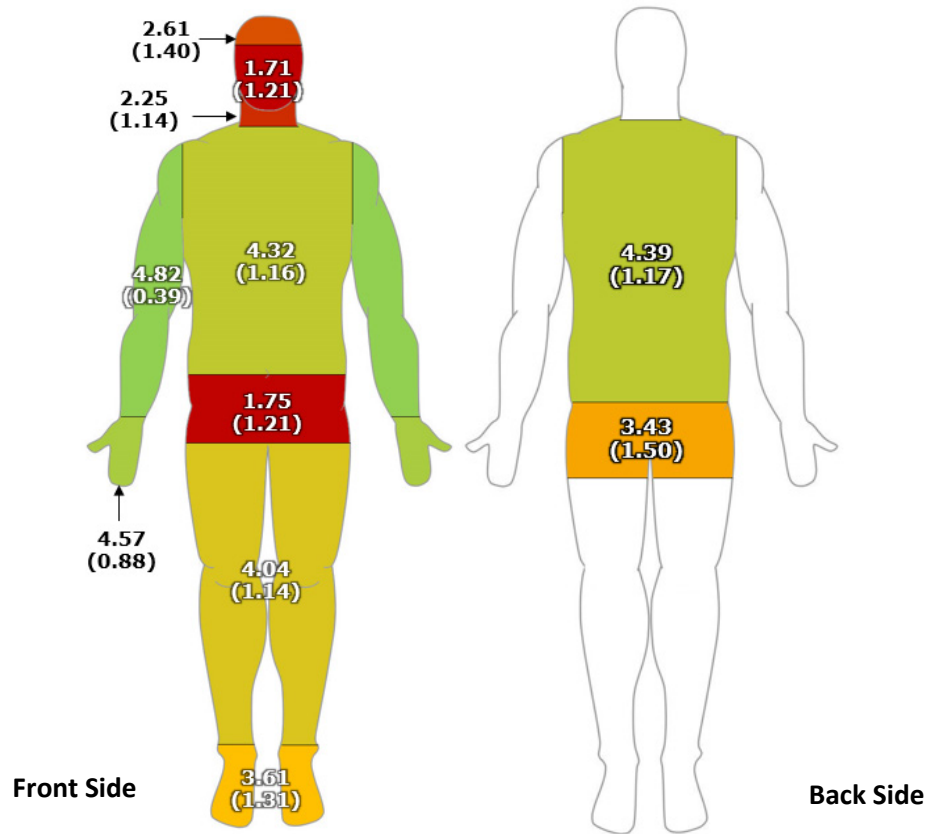
Figure 27 A heat map of users' acceptability of receiving novel haptic feedback in various body regions.

4.3.6 Challenges and Opportunities of Delivering Haptic Feedback Using serpentine-shaped robotic appendages

In this section, we analyze a number of opportunities and challenges with respect to serpentine-shaped serpentine-shaped robotic appendages. The opportunities and advantages are as follows:

Varied Feedback Locations: Unlike other vest worn devices, HapticSerpent can deliver feedback to areas beyond the torso. For example, the neck area, upper arms, and forearms (As shown in Figure 8). + Extended Feedback: With exchangeable end effectors, HapticSerpent can deliver a variety of haptic feedback (Figure 25). This capability not only expands the range of haptic feedback types, but also allows it to accommodate distinct user preferences or ergonomic differences. For instance, taller users may use bigger or longer end effectors so that the robot arm may reach the whole torso.

Multifunctional: With exchangeable end effectors, our robot could be utilized for a variety of experiences beyond haptic feedback. For instance, feeding the user in VR, or delivering wind-effects to the user's face (Figure 9), are some of the potential VR experiences. + Varied Applications: Feedback can be used for purposes beyond VR experiences. For

example, drawing the user's attention to hazards and emergencies, like earthquakes, or for smartphone notifications. Haptic feedback can be utilized for breaking VR immersion.

There exists a number of challenges and disadvantages in using serpentine-shaped robotic appendages to deliver feedback, which comprise the following:

Visuo-haptic synchronization: Despite its versatility, the serpentine morphology imposes several limitations. Since the robot arm must move to different points to apply feedback, there is an unavoidable delay in orienting and moving the arm. This is especially prevalent if the visual feedback in VR is much faster or very frequent, such that it outpaces the capability of the robot arm synchronously to deliver haptic feedback in accordance with visual stimuli.

Simultaneous Haptic/Tactile Feedback: Another shortcoming of the serpentine morphology is its incapability to deliver multiple haptic feedback impulses in parallel. Thus, further morphologies should be investigated, such as a multi-arm robot. - Unintended Feedback: As most users utilize VR joysticks, the robot arm could collide with the users' hands, resulting in unintended haptic feedback. Moreover, quick user movements, such as leaning forward, could result in overshooting intended feedback force magnitude or location. Such issues require further optimization in the wearability and mechanical design.

Calibration: An easy and precise calibration method ensures a replicable and high-quality user experience. A quick calibration method is important for instantly adapting to differences between users. Moreover, thick clothes, like jackets, could absorb delivered feedback, thus, feedback should be adapted to variance in users' clothing. Lastly, delicate areas, like the neck present calibration and safety challenges for haptic feedback.

4.3.7 Conclusion

This case study focused on HapticSerpent, which is wearable haptic feedback robot. We presented our initial design direction, followed by an analysis of advantages and limitations. The results of our initial evaluations overall encourage us to pursue further development and the survey results are intriguing to explore further. Especially, survey results provide in-depth insights towards which experiences are acceptable in which location, which can be used to for further probing each individual feedback type. HapticSerpent should be further mechanically improved in terms of actuation and design. Specifically, better mechanical design would both improve feedback control and ergonomics. Therefore, this case study presents the foundation on which upon we extend through the development of the HapticHydra, presented within the case study HapticSnakes.

The novelty of HapticSerpent was encouraging for us to further utilize the robot as a platform to conduct further work. Therefore, HapticSerpent is utilized as platform to conduct deeper analysis and evaluations of using serpentine-shaped robotic appendages as multi-feedback wearables. Such findings allowed extracting insights about the potential novel experiences and understand the methodology of designing cohesive user experiences (as highlighted in RQ3). Further details are in section 4.5 HapticSnakes.

4.4 weARable

4.4.1 Introduction

Wearable robotics have long been researched as platforms for various applications, such for rehabilitations, exoskeletons or haptic feedback. Supernumerary robotic limbs are a sub-category of wearable robots that equip the user with additional robotic appendages that can be used for a variety of interactions. However, controlling this form of wearables is an

essential challenge; since most of these wearables lack efficient control interface or provide context-specific user interfaces (Dementyev, Kao et al. 2016, Kao, Ajilo et al. 2017, Leigh, Agrawal et al. 2018). While these control methods may be efficient, their narrow scope of implementation and optimization makes then inapplicable to a changeable and dynamic usage context, such as the daily interaction context.

Advancements in Augmented Reality (AR) have demonstrated a large potential for applying such technology across a variety of applications. Modern platforms used for AR, like smartphones or head-mounted displays (HMDs), comprise numerous input methods and sensors that can be used as base to deliver rich user experiences. Therefore, AR is a highly potential medium for robotics in general, and especially wearable robots.

In order to address the interaction genericity challenge of wearable robotic appendages, we developed weARable, which is a system comprising an AR HMD and a multipurpose wrist-worn serpentine-shaped robotic appendage. We utilize weARable as a platform to investigate the architecture needed to develop cross-device experiences, explore potential user experiences combining AR and serpentine-shaped robotic appendages. First, a framework is presented for efficient development of integrated AR and robot experiences. The integration framework offers the flexibility of both AR and robot control systems via a publisher-subscriber service model made available over the network. We proceed by exploring the design space of potential experiences combining AR and wrist-worn serpentine-shaped robotic appendages, which include AR robot pose control, robot status display, AR menu navigation with robot shape-change, and a robotic haptic interface for an AR media player, and agent based experiences. Similar to previous studies ((Pedersen, Subramanian et al. 2014, Teyssier, Bailly et al. 2018) a preliminary user study was conducted to explore the usefulness and user impressions about potential user experiences

The contributions of this work include the following: 1) A flexible framework for developing cross-device applications involving wearable robots and other devices (especially AR HMDs). 2) A design space for multipurpose use, comprising various experiences that combine AR and a wrist-worn serpentine-shaped robotic appendages. 3) Preliminary evaluation results based on the developed user experiences of the design space.

4.4.2 Related Works

Augmented reality allows for digital information, such as text, graphics, or 3-D models, to be rendered within real world contexts. As AR is essentially an output method, AR is supplemented with various interaction modalities (Kölsch, Bane et al. 2006, Lee, Billinghurst et al. 2013), such as voice commands or hand gestures. Researchers have investigated using AR for maintenance (Schwald, Laval et al. 2003, Henderson and Feiner 2011), where visual and auditory instructions can easily be relayed to users in the field. Reality Editor (Heun, Kasahara et al. 2013) and Smarter Objects (Heun, Stern-Rodriguez et al. 2016), show how AR can serve as an effective medium for controlling smart environments. For example, visualization of mappings among smart objects and making alterations to suit their control requirements. Their work also showed how users can control smart objects with AR using a variety of interaction methods.

Previous works on using AR for robotics have also shown promising application domains. Various works investigated the use of AR to compliment interaction with robots. Several works utilized AR for displaying robot intentions. For example, to show the motion trajectory to be executed by the robot or future state of a robot upon executing specific actions, where such visualizations are digitally shown prior to actual execution of intended actions (Chadalavada, Andreasson et al. 2015, Rosen, Whitney et al. 2017, Walker, Hedayati et al. 2018). Visualizations have also been investigated for robot controls, such as to provide

visualizations to support teleoperation of a robot (Hashimoto, Ishida et al. 2011, Cheung, Eady et al. 2017, Williams, Tran et al. 2018). Moreover, various works utilized AR enabled devices (e.g. smartphones, tablets or HMDs) for environmental tracking, where the devices are used to map and track the environment and the robot, to enable operators to easily compose motions or control the robot to execute specific tasks (Heun, Kasahara et al. 2013, Alonso-Mora, Siegwart et al. 2014, Andersson, Argyrou et al. 2016, Cheung, Eady et al. 2017). Some research into digital augmentation of robot form provided robots with previously unavailable functionality, such as robot gestures or deixis (Holz, Dragone et al. 2009, Williams, Tran et al. 2018, Williams, Bussing et al. 2019). Anthropomorphic aesthetics such as faces, or hands can be added to robots to allow for more human-like interaction.

In contrast to existing works, weARable focuses on exploring cross-device interactions using AR with wearable robotic appendages, which is a domain that have not been explored in previous literatures. Moreover, we focus on multipurpose usage within daily usage domain, which require a variety of interaction methods. These challenges and domains have not been emphasized in any surveyed literatures.

4.4.3 The Design and Implementation of weARable

The main design objective of our work is to explore how can we design cross-device interactions comprising AR and snake-shaped robotic appendages. Therefore, we first developed a framework to integrate AR HMDs with wearable robots, with the objective of enabling proficient development of integrated AR and wearable robot experiences for coherent user interaction. The use of AR, and related interaction modalities, enables the robot to function independently of the user's physical limbs, and allows for the entire system to be used in a mobile context. We define our approach for each component, including hardware, software and integration implementations within the next sections.

4.4.3.1 Robot Design and Control

Mechanical Design: Our robot consists of six interlinked Robotis Dynamixel AX-12A servomotors (stall torque 1.5 Nm) (Robotis 2019). The servomotors are fastened together using plastic brackets. We have chosen this robot configuration to maximize the number of useful robot poses, making it flexible enough to be used in a variety of applications. The robot is mounted on the user's wrist using a plastic bracelet and a Velcro strap to provide a stable base. The total weight of the robot is 500g and the length at full reach is 300 mm.

Control Unit and Power: Our robot control software is deployed on a GPD WIN portable minicomputer (GPD 2019) Figure 28, which connects to the robot via USB cable interface. The robot is powered by a lithium polymer battery, which allows for approximately 25 minutes of robot operation.
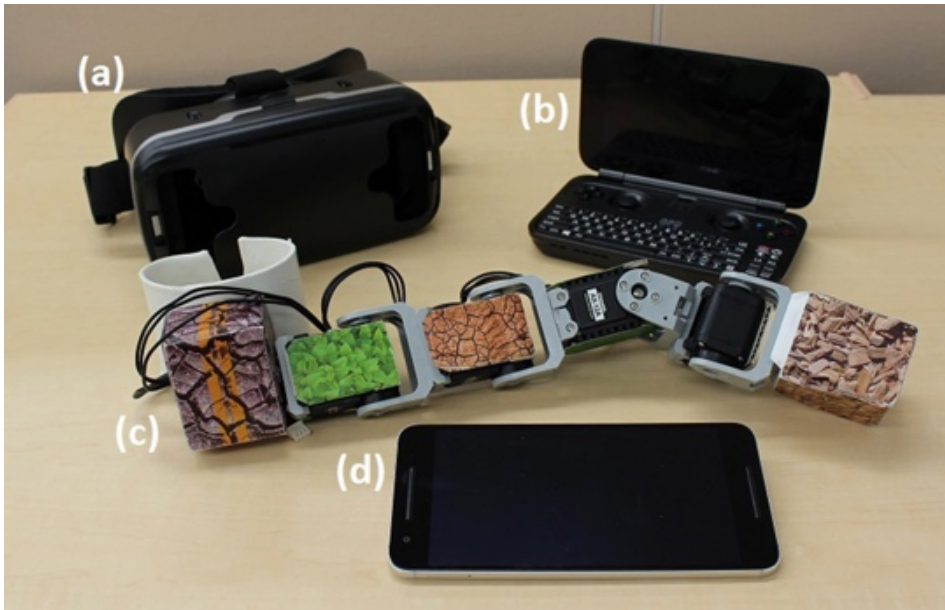
Figure 28 Hardware components of weARable: (a) AR enclosure, (b) GPD WIN, (c) wearable robot with attached fiducial markers, and (d) Android phone

Control: Our robot control software was developed in C# and utilizes the Robotis SDK (Robotis 2019). This software abstracts all robot communication and control functionality and provides a unified servo class interface through which servos can be easily accessed. We designed a graphical user interface (GUI), which allows us to interact with the abstracted information Figure 29. Through this GUI we are able to monitor and control the robot and each individual servomotor. All servomotor attributes and movement controls are made available over the network.
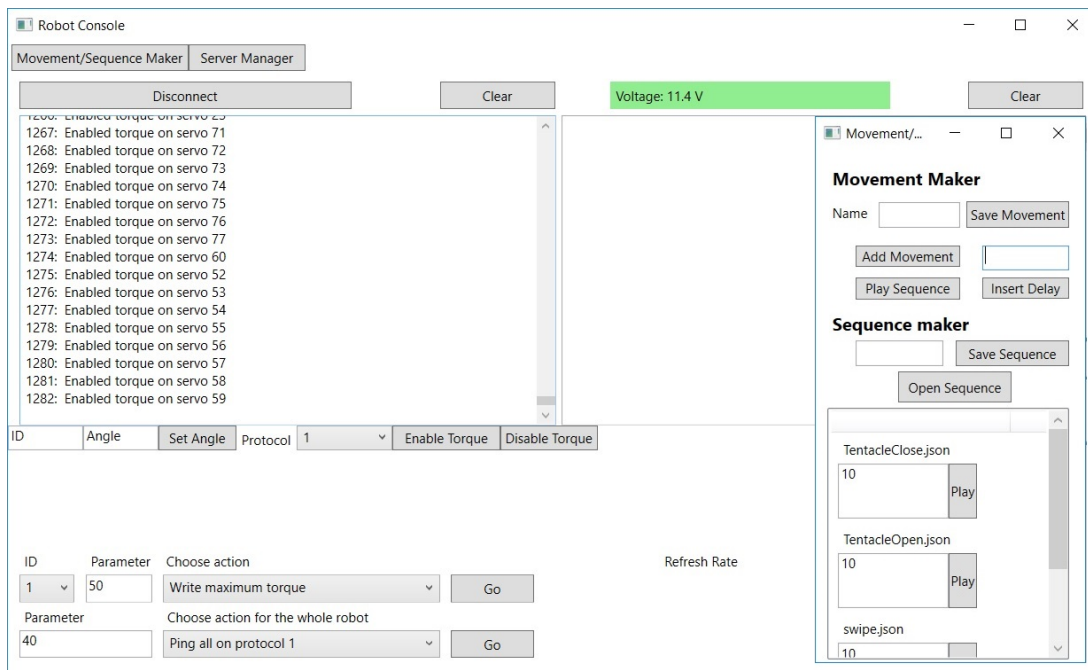
Figure 29 the control software GUI. Motors can be controlled manually within the interface. The smaller window to the right, allows movements to be captured and saved. These movements can be executed singularly or as sequences.

4.4.3.2   AR System Design

Augmented Reality and Head-Mount Display Software: We developed an AR application using Unity3D (Unity3D 2019) and Vuforia (Vuforia 2019). The user interface is controlled using gaze, allowing the user to simply look at objects to interact with them. Here, gaze is configured for the user to focus on an object for two seconds in order to perform an operation. For spatial registration, we utilize fiducial markers (Figure 28). We used Fiducial markers as they are easily detectable by the AR system to localize and register contents on or around the robot, providing inside out tracking capabilities. In the head-up display (HUD) mode, our application also displays AR content but without spatial registration. In this scenario, pieces of AR content are fixed within the user's field of view as in Figure 33 b. By providing both fiducial markers and a HUD, our system can accommodate and provide various interaction experiences. These modes make the system context adaptive in situations where users are not able to maintain constant visual contact with the robot.

Hardware: The HMD is a generic 3-D AR/VR smartphone enclosure fitted with a Google Nexus 6P Android Smartphone (Figure 28) running our AR application. We chose this implementation as it is common, relatively light weight and can easily be deployed in future systems without having to cope with changes to the smartphone hardware.

4.4.3.3   Integration Framework

Our integration framework relies on WebSockets (Websocket.org 2019) to implement a publish-subscribe messaging pattern (Kaiser and Mock 1999) between the robot and AR system, as illustrated in Figure 30. Various systems can subscribe to services based on required functionalities. In our system, the robot controller computer is the publisher, and the AR system is the subscriber. Two types of WebSocket services are exposed, these enable the AR system to issue commands for the robot and receive feedback about the robot. We categorize the services as follows:

1) *Control services*, which allow clients to invoke servomotor controls, such as turning to specific angles, altering speeds, or setting maximum torque limits. Movements and movement sequences are also invoked via control service.

2) *Feedback services*, which broadcast robot information at specific rates and on events. For instance, applications can receive regular updates of servomotor attributes, such as angles, temperatures, maximum torque limits, and loads.

Messages exchanged with services are created using JavaScript object notation (JSON) (JSON 2018). We chose this notation as it is an easy and robust method of encapsulating data. Each control message comprises message type, intended command, servomotor IDs and other parameters. Similarly, each feedback message comprises feedback type and related data. For example, to rotate servomotor 11 to angle 90 degrees, at a speed of 50%, we send:

```
{"Movement":[{"ID":"11","protocolVersion":"1", "ServoType":"AX 12A", "angle":"90", "speed":"50"}]}
```

Message structures can easily be defined by developers to match specific application needs. For instance, a message can be sent to control or to request feedback from multiple servomotors, or to impose specific torque or angle limitations on specific servomotors.

The publisher-subscriber messaging pattern provides numerous advantages. Several services could be created for various control or feedback requirements, such as controlling specific servomotors or reading temperature feedback. Such segregation can provide scalability and reliability, enabling different services to run as separate processes or threads (Kaiser and Mock 1999). Moreover, this structure can accommodate changes to the selected hardware, such as changing the robot morphology, structure, servomotor types or HMD. The

segregation of manufacturer specific robot controls by means of invoked services allows the robot control software to be altered or upgraded without affecting the network interface. Accordingly, this enables developers to experiment with different AR interaction and spatial registration methods without affecting the robot software. This model also allows multiple devices to subscribe and interface with multiple robots, which enables a flexible platform for experimenting with various device or robot configurations.

Our framework addresses the challenges of integrating AR and wearable robots, especially for creating interactive user experiences. Previous work focused on demonstrating potential AR use cases, without emphasizing the underlying implementation infrastructures (Hashimoto, Ishida et al. 2011, Williams, Tran et al. 2018, Williams, Bussing et al. 2019).

Other similar frameworks focused on different application domains and robot types, such as industrial robots and applications (Andersson, Argyrou et al. 2016). ROS (ROS 2019) is middleware for robotics and is mainly concerned with the integration and control of different robotic components, but differs in scope from our framework. Our framework targets the creation of experiences for AR and daily worn robots. For example, our framework can accommodate different interaction modalities, AR tracking methods, and robot morphologies. These features significantly contribute to research efforts within relevant fields, such as human robot interaction and user experience design.
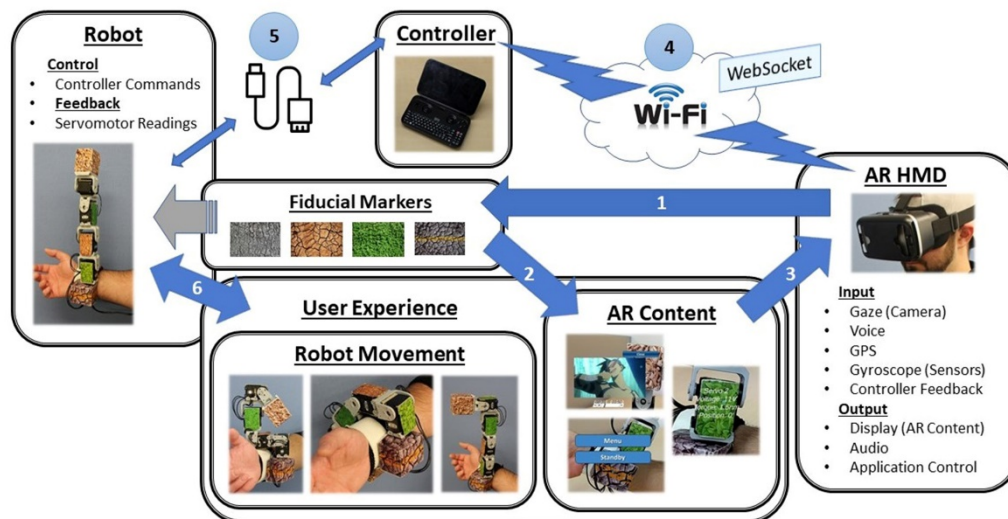
Figure 30 this diagram illustrates an overview of our framework. The workflow runs in numeric order from (1) to (6) or reverse numeric order from (6) to (3). For Example: 1) AR HMD tracks the fiducial markers fixed to the robot, 2) Relevant AR content is displayed on the markers, 3) gaze interaction with the AR content is performed, 4) Application instructions are sent to the controller service via WiFi, 5) Service messages are translated to robot movements, 6) Robot movements are performed.

4.4.4 Design Space

4.4.4.1 Interaction Paradigms and Experiences

Our system is mainly designed to address and embody a number of challenges and expectations. The first challenge is to address the need for users to realize and control various inner attributes. The majority of reviewed multipurpose robots lack proper input and output methods to indicate other inner state (Nakagaki, Follmer et al. 2015, Dementyev, Kao et al. 2016, Leigh and Maes 2016). Therefore, our system aims at allowing users to realize and control fundamental robot attributes, such as servomotor speeds or postures. Second, as multipurpose is an essential design expectation, the second objective is to allow users to select and switch among different modes of operations, or robot purposes. We grouped these

interaction experiences under *intrinsic interactions*.

Digital interactions are the second category of interactions that our design space is concerned with. In this domain, we investigate a number of interaction experiences that seamlessly combine the robot and AR, such as being an always available tangible user interface or haptic feedback. Accordingly, we present a number of applications that reflect different interaction potentials enabled by AR and a wearable robot.

An important insight extracted from Orochi's evaluations is the user expectation of the robot's interaction paradigm, namely as a tool or as a companion. Similarly, previous works in HCI have classified and presented similar interaction paradigms (or roles) various systems can partake (Beaudouin-Lafon 2004, Leigh and Maes 2016, Teyssier, Bailly et al. 2018). Therefore, we extend this concept in the design of our system by incorporating them as the following:

1- *As a tool*: serpentine-shaped robotic appendages act as an augmentation interface to enable physical and digital interactions with the real world. Based on Orochi's evaluations, explicit interactions are a major expectation of this interaction paradigm, where such interaction methods rely on the users to initiate and control the experience. We created a number of experiences under this paradigm and presented them under *Physical Interactions*. These interactions utilize AR as a medium to initiate, support and execute various physical manipulations on surrounding objects.(Hussain, Spagnoletti et al. 2016)

2- *As a companion:* serpentine-shaped robotic appendages are expected to be highly intelligent and autonomous, initiating various actions with minimal or without user intervention. We created a number of experiences and classified them under *companionship*. A variety of digital interactions are presented, where AR is shown to play a critical role in enhancing the aesthetics and extending feedback capabilities of the robot.

The following subsections describe the design space that comprises a number of interaction experiences (illustrated in Figure 31).
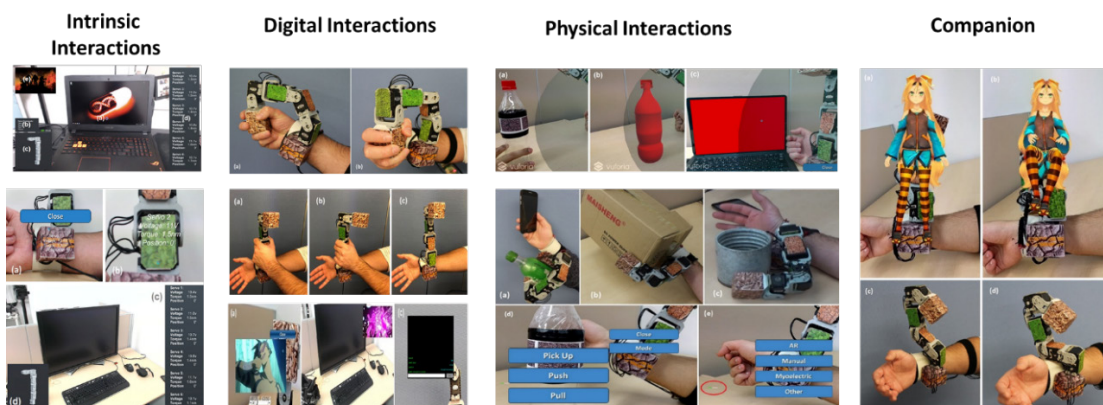
Figure 31 overall view of weARable Interaction Space

4.4.4.2 Intrinsic Interactions

This domain of interactions constitutes scenarios where users need to visualize or control intrinsic attributes. First, users should be able to control robotic attributes, like current posture, servomotor speeds or torques. Therefore, we used AR to visualize different menu items similar to WIMP (Jetter, Reiterer et al. 2013), where users can gaze at different items to set them (Figure 32). Second, an essential usage scenario is to enable users to switch among different modes of operations (e.g. to use the robot as an always available interface or as an SRL). Two experiences were developed to portray the experiences in this domain:

1- The display of detailed information for each servomotor component. Information such as servo rotation, voltage, temperature, and torque values are available for display. This information is also accessible in two further forms; spatially registered or HUD mode. When the device is within view, the user gazes at a desired component and the respective information is overlaid, in AR, above that selected component Figure 32 (left, (a) and (b)). When the device is out of view, the details of every available component is fixed to the right of the user's HUD (c). A 3-D model of the current robot hardware configuration Figure 32 (left, d). This model, displayed in the bottom left of the user's HUD, changes shape along with the physical robot. This enables the user to know the current robot shape or state whenever the device itself is not within view.

2- This application demonstrates how a serpentine-shaped robotic appendage can be controlled to switch among different modes of operations or applications, which addresses the challenge of allowing users to visualize and switch between different modes of operation. As shown Figure 32 (right), we developed a menu that allows users to switch among different modes of operations in AR. The menu may comprise additional functionalities, which users can easily select, utilize or switch to other applications. We used dwell-time (Müller-Tomfelde 2007) as a mean to interact with various menu items through head-gaze (Minakata, Hansen et al. 2019). Moreover, various selections of the menu items will yield changes in the robot pose (as shown in Figure 32 (right)), therefore providing haptic and shape-shifting feedbacks upon selection of various experiences.
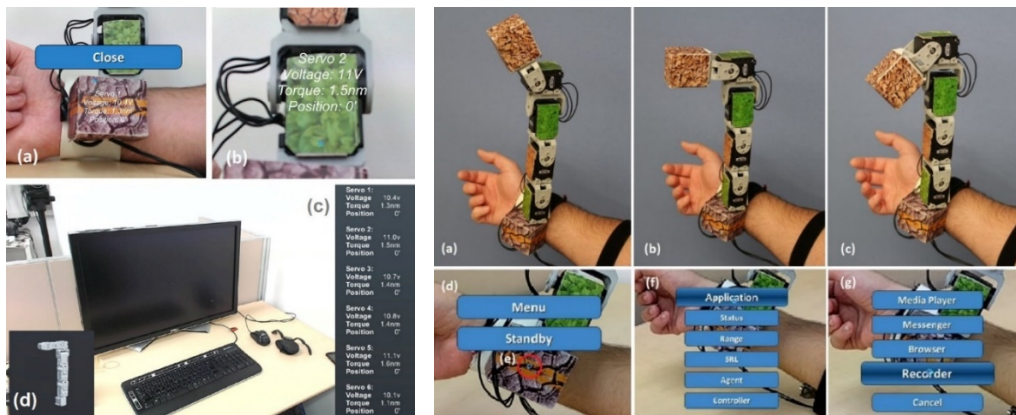
Figure 32 Left) Various intrinsic attributes are shown with (a,b) spatial registration and (c,d) without spatial registration. When displayed without spatial registration, the information floats and follows the user's field of view. Right) Using the gaze-cursor, weARable can move and take different shapes to convey browsing or selection. The user can browse and select applications (d) the start menu (represented by (a)), through (f) the main menu (represented by (b)), to (g) the app menu (represented by (c)). Similarly, each application has a designated pose representation.

Overall, the developed experiences provide users with a method to visualize various inner attributes, as well as switch among different possible experiences. Therefore, they address essential usability challenges with serpentine-shaped robotic appendages, as they allow users to realize the intrinsic state of the robot, as well as realize and select various available experiences, applications and functionalities possible by the serpentine-shaped robotic appendages.

4.4.4.3 Digital Interaction

This domain covers experiences in which wearable is used to interact with digital contents or other software, either embedded within the AR HMD or with other capable external systems. In this section, a number of experiences are presented and discussed to showcase how weARable can be used as an always available interface for digital services.

The first experience is the haptic interface, which allows users to interact with digital systems through physical manipulation of the robot's joints, similar to tangible user interfaces (Fortmann, Root et al. 2016, Cheung, Eady et al. 2017). To illustrate a usage scenario, we developed a media player and a textual instant messenger application (shown in Figure 33).

Figure 33 Interaction with digital contents. (a & b) Media Player application. (c) Instant Messenger application. Both applications can be deployed with spatial registration to the robot or to the HMD (i.e. HUD).
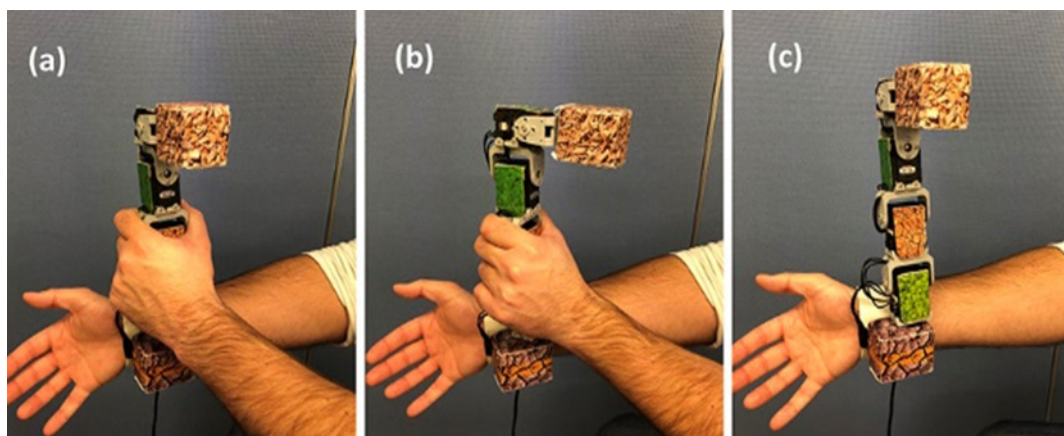
Figure 16 shows the control sequence for the Media Player skipping to the next audio, image or video file. These control methods are a requirement during HUD mode operations due to the hidden AR controls. Here the user would (a) grab the device above the base marker, and (b) rotate counterclockwise until the device reacts to the motion and (c) automatically returns to its original position. Our robot control and integration software then forward the registered movement to the AR application and the next file is rendered in the player. The same process is followed to revert to a previous file, the only difference being the opposite (clockwise) rotation of the device by the user.
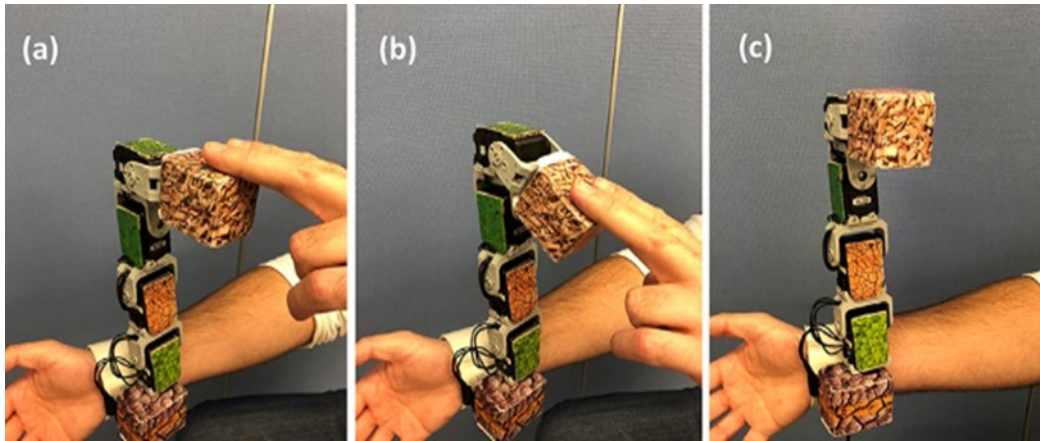
Figure 17 shows the control sequence for the pausing and resuming of media. The user would (a) apply pressure to the device's top marker, and (b) rotate downwards until the device reacts to the motion and (c) automatically returns to its original position. As above, our software forwards the instruction to the AR application and the media is paused (or resumed if already paused).

4.4.4.4   Physical Interactions

We explored a variety of methods in which AR can support the physical interactions, and we grouped these methods into two main categories. First, we discuss methods on which an AR system can contribute to controllability of the robot. The second aspects are related to supportive methods, where the sensory information and visualizations of AR can assist users during physical manipulations. We discuss each category in the next paragraphs.

AR can support the controllability of wearable appendages in a variety of methods. From the menus, users can select the *"SRL mode"* allows users to physically interact with their environment via the wearable robot (Figure 34). Different designs could allow for the device to be used as an additional arm, leg, finger or even a tail. Interactions can thus range from any generic action in place of a user's natural limbs, to interacting with objects or in situations with which a user would otherwise be unable handle, such as grabbing a large object single handedly. Moreover, advanced interactions which may be difficult or possibly dangerous for normal human interaction, such as the handling of objects that are larger than the user could manage, handling objects of extreme temperature, or allowing for single-handed operations usually requiring both hands.

Control methods of the physical interaction mode is based on the AR menus and is based on the *tool paradigm*. We implemented two categories of interactions. First, as shown in Figure 34 d, the user would look at a specific object they want to manipulate, after which an AR menu would pop-up to display possible interactions. This mode of interaction implements higher level of autonomy as it relieves the user from the specifics of controlling the robot to correctly execute the actions. However, this interaction assumes that the target object can be recognized and tracked in real-time. In order to demonstrate this method of control, we placed fiducial markers over the bottle. Future implementations can utilize advances in object recognitions to realize this interaction method.

The second domain of physical interactions is implemented through a variety of manual interaction methods. First, we implemented an interaction method based on myoelectric in a similar fashion to previous works ((Wu and Asada 2014, Leigh and Maes 2016). In this mode, the robot is manually controlled through hand gestures to wrap/unwrap its body around objects (Figure 34 c). The second manual control methods uses the AR menu to invoke pre-recorded robot poses, which can be used to manipulate physical objects. (Figure 34 c). Since these control methods exhibit low levels of autonomy, they require the user's

constant attention to control the flow of physical manipulations and ensure their success.
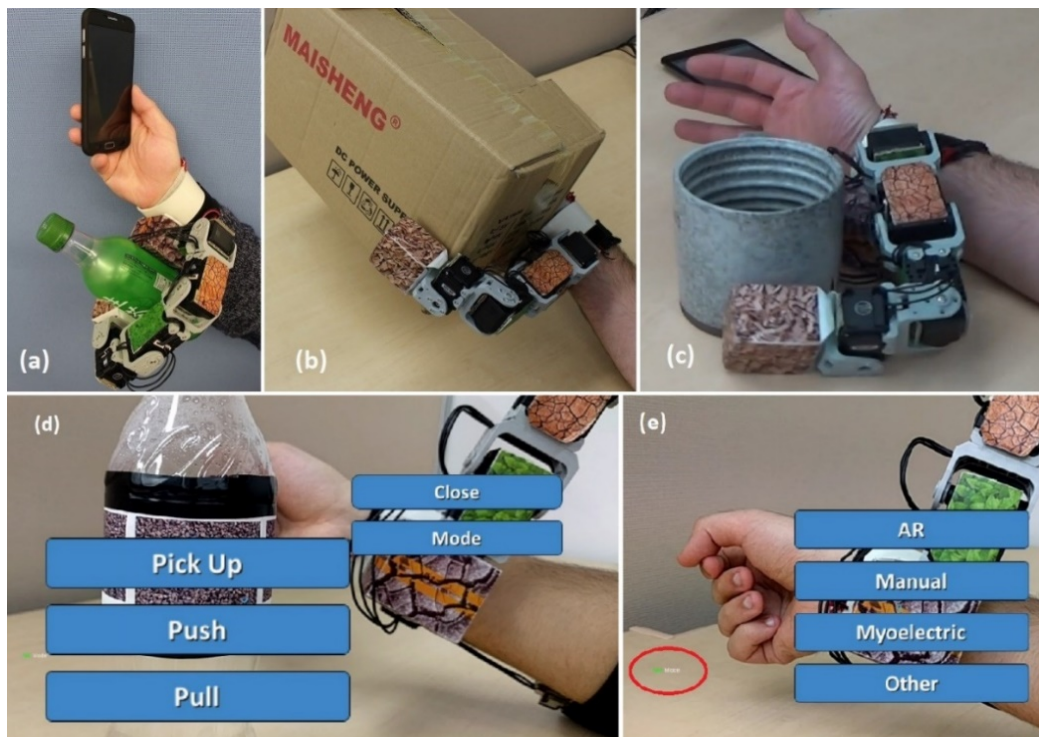
Figure 34 Examples of SRL mode interactions. The robot can be used for a variety of physical interactions, such as to hold more objects or large objects in a single hand (a,b). Based on the tool paradigm, we implemented a variety of control methods. First, (d) demonstrates and interaction method based on AR menus, where the target object and target action can be selected and then automatically executed by the robot. The other control methods include myoelectric synergetic controls (e,d) and manual controls based on prerecorded robot poses that can be selected and executed through the AR menu.

AR can provide numerous advantages to physical interactions. To illustrate this, we implemented an AR application that allows users to visualize the workspace of the robot. The workspace is typically the accessible range on which the robot can carry-out physical manipulations. Such ability allows users to know what the range of the robot is and which objects can or cannot be manipulated (as shown in Figure 35). Furthermore, the embedded camera and CPU of the HMd can be used to recognize and we extended the visualizations of the workspace to so that it comprises other objects. For examples, Figure 36 shows, we use the embedded camera to recognize the location of surrounding objects and the robot, enabling users to know when an object is within range of physical interaction or not. Since the robot is kinematically dependent on the users' hand pose, such experience is crucial for users in assisting users to properly situate their hands during physical manipulation tasks.

Overall, we presented a number of experiences that illustrates how embedded hardware and sensors in the HMD can be used to support physical manipulations. We provided several examples where the HMD was advantageous for selecting various interaction mediums (myoelectric, prerecorded actions…etc), as a control method (interaction menus) and to support physical manipulations through visual cues (as in the workspace). These aspects provide evidence towards the superiority of using AR HMDs as comprehensive interaction modalities that offer flexible and robust potentials for visualization and control.
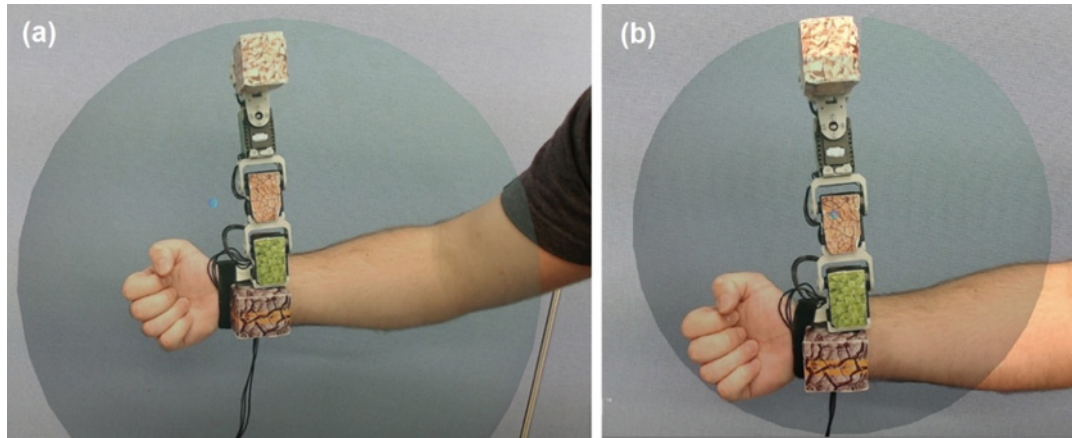
Figure 35 the workspace visualized the accessible robot range where it can carry-out physical manipulations. a) The workspace of the entire robot, b) the accessible workspace of the robot when servomotors 2-5 are moved.
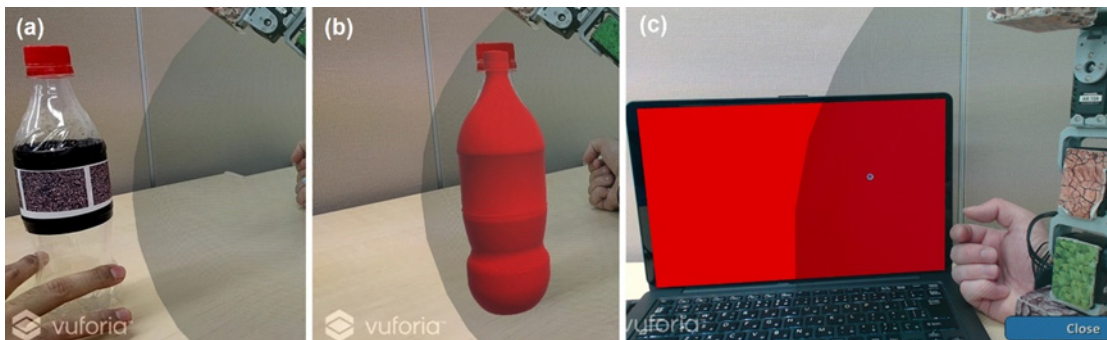
Figure 36 this figure illustrates how the workspace information can be combined with object recognition capabilities to support physical manipulations. a) Since the workspace of the robot is tracked and known by the HMD, the HMD can infer whether a tracked target object is within range or out of range. If the object in range, the object can be highlighted as shown in (b,c). This ability allows users to easily situate their arms to manipulate various objects.

4.4.4.5   Companionship

This category of interactions extends existing works on interface agents and embodied agents (Holz, Dragone et al. 2009, Kashiwabara, Osawa et al. 2012) which are concerned with experiences that offer various forms of artificial intelligence for initiating or executing various tasks. In our case, the companionship experience is a form of assistant, thereby providing similar functionalities to digital assistants like Siri(Apple 2019), or Google Assistant (Google 2019) the user may interact with the agent to accomplish tasks and receive information. Nevertheless, a key difference between our implementation is the physical embodiment of the agent through the wearable robot. In this section, we investigate a number of experiences involving a companion character that is embodied through the wearable robot.

The companionship experience is able to convey a variety of interactions with digital contents, including haptics and shape-shifting experiences that both combine AR and robot. The companion character is animated 3-D character model, called Unity Chan (Unity-Chan 2019), which is rendered over the wearable robot. The model and robot movements are synchronized (Figure 37), with interactions directed at one form also affecting the other. These combined factors have an anthropomorphic effect and promote the impression that

the user is interacting with an intelligent physical entity.

The companion character responds to touch and gaze controls and is able to relay various external-system notifications and feedback to the user in three main modalities: 1) auditory, 2) haptic or 3) shape-shifting. Accordingly, we developed experiences that convey these modalities through the companion character. First, the companion character can convey system notifications, such as system-triggered actions (e.g. to indicate boot-up sequence or welcome greeting). In such scenarios, the agent waves at the user and greets them verbally, thereby indicating that the system is ready for use.

Additionally, users can also trigger various actions. For example, users can physically push the robot to dismiss notifications, where such action is accompanied by flinches and winces as a reaction to being dismissed. In such experience, physical forces applied to the robot are reflected upon the character, further enhancing the user's perception of an interactive intelligent agent. Another example experience is haptic feedback for the instant messaging application, where the agent physically tap the user's arm to indicate incoming messages. When applying the tap, the agent physically leans forward synchronously with the robot, which gives the impression that the user is being tapped by the character.

Overall, these experiences provide intriguing interaction potentials that seamlessly combines virtual companionship characters with wearable robots. This integration of a powerful visual medium and expressive physical interactions allows a virtual character to physically come to life. This embodiment of the character can be extended with various forms of physical interactions involving objects, and not limited to digital interactions.
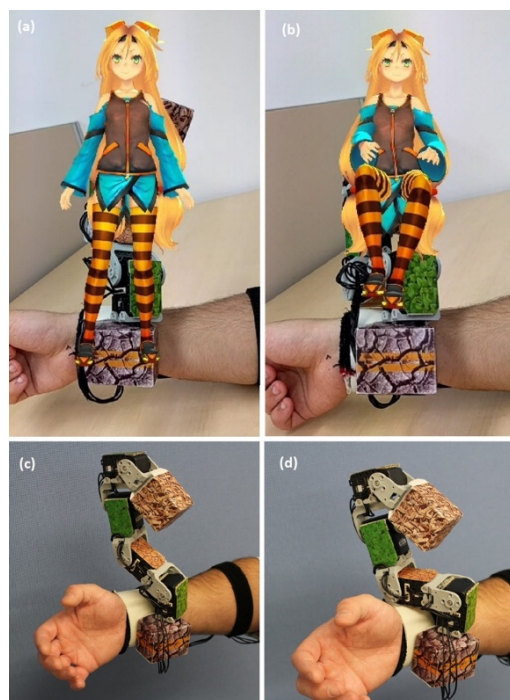
Figure 37 : The synchronized movement of 3-D model and robot performing 'Sit' operation.

4.4.5   Preliminary Evaluation

Objective and Participants: Similar to previous works (Pedersen, Subramanian et al. 2014, Teyssier, Bailly et al. 2018), we designed a preliminary evaluation to gauge the usefulness of the interaction experiences as well as get initial user impressions of the design space experiences. Therefore, we invited 7 college students, aged between 21 and 29 who indicated that they both know about AR from popular smartphone applications, and wearable robots through different sci-fi media and research.

Procedure: The evaluation began with a brief introduction of AR and our robot. First, we set-up the system, users had to wear the HMD and the robot as shown in Figure 38. Next, each participant was briefed and shown the various experiences of our system, after which they had the chance to try and experience each of the applications by themselves. Upon finish each experience, each participant took a short post-experience survey about that gauged the usefulness and general impressions of such experience. After finishing all the experiences, participants took a post user-study questionnaire and a semi-structured interview. The user study lasted 60 minutes per participant.
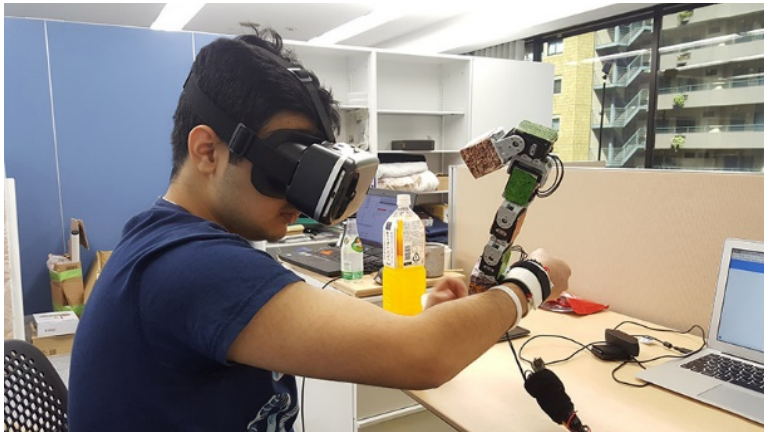
Figure 38 A participant during the user study as he experiences AR interactions with the wearable robot.

4.4.6 Results and Analysis

Similar to previous works (Pedersen, Subramanian et al. 2014, Teyssier, Bailly et al. 2018), We asked participants to rate each experience on a Likert-scale (1 is not useful, 5 is very useful). We present the corresponding usefulness ranking of each experience below:

Intrinsic Interactions - Shape-Changing Menus: Participants had mixed feedback for this application. Although participants it might be useful to portray menu selections as robot poses (m=3, SD=1.15), some participants indicated that robot movements were subtle. Therefore, the movements speed, durations, or postures should be improved so that users can distinguish among different menu selections.

Intrinsic Interactions -Device Status: Participants generally thought that this experience is very useful (m=4.14, SD=1.07). They suggested reducing the information to that which could be more useful to an end user, such as temperature and battery readings or failure notifications. The HUD was slightly more preferred (m=4.43, SD=0.54) over viewing information on the robot through the fiducial markers (m=3.29, SD=0.95); as users had to look very closely to the robot so the fiducial markers are recognized. We believe that a better tracking system could contribute to overcoming this issue.

Physical Interactions - Workspace: Participants thought this application was very useful (m=5, SD=0). They though this application is essential for enabling them to realize reachable regions for carrying out physical manipulations. Moreover, some participants suggested adding a pop-up notification to state when they are too near the device to properly view the workspace.

Physical Interactions - SRL Mode: We focused our investigation on the SRL menus, since myoelectric and manual control method have been investigated in previous works (Hussain, Salvietti et al. 2016, Leigh and Maes 2016). Overall, participants feedback was positive about this application (m=4.4, SD=0.55). They shared many possible use cases for the application in their day to day lives, the most resounding of which was simply to carry objects so as to free up their natural limbs for other tasks. Other more advanced tasks would require

alterations or adaptations to the current design.

Media Player & Messenger: Participants found these applications very useful (*m*=4.4, SD=0.55), and they were highly in favor of both interaction methods (*m*=4.8, SD=0.45). Participants also though the HUD was highly useful, as it provides the freedom of interacting with contents without maintaining eye-contact with the worn robot.

Companion: Participants generally found this application very novel and useful (*m*=4.8, SD=0.45). Participants mentioned that interacting with the companion character in multiple modalities was very enjoyable. Participants thought the character could be an anthropomorphic virtual assistant, where she can provide notifications, reminders and search functionalities.

We finally asked the participants to rank the experiences from most to least liked (6 is most liked). The results are as follows: companion (m=5.4, SD=2.30), SRL Mode (m=4.6, SD=1.14), Media Player & Messenger (m=4.1, SD=1.73), Workspace (m=3.2, SD=0.84), Shape-Changing Menus (m=0.6, SD=0.55) Status (m=0.4, SD=0.55). These results indicate that the companion, SRL Mode and media player & messenger experiences were highly enjoyable. Overall, the results show that all the experiences were found to be of great use, despite the technical challenges associated with fiducial markers.

The hardware was also evaluated in the questionnaires. Participants thought that the robot was quite comfortable (*m*=3.4, SD=0.89) but mentioned that available tasks could benefit from a slightly smaller form factor. Moreover, users thought the wearable should be lighter in weight, especially if worn and used over extended periods of time (*m*=2.4, SD=0.55). The used HMD received mixed impressions (*m*=3.0, SD=1.0), and the AR performance was given (*m*=3.4, SD=1.14). Participants thought the AR experiences were generally responsive and intuitive (*m*=4.2, SD=0.69).

4.4.7 Conclusion

In the future, daily worn robots will play a larger role in our lives. An essential challenge of realizing these wearables is interaction and control, especially as most robots comprise a minimal amount of I/Os to enable cross-contextual multipurpose use. We bridge this gap with a framework that enables the development of applications and experiences that combine AR and wearable robots. We accordingly use our framework to construct a design space of possible experiences under two main interaction paradigms: as a tool and as an agent. Accordingly, the design space is constructed to demonstrate experiences for interactions with the robot intrinsics, digital interactions, physical interactions and companionship. We follow with a preliminary evaluation to gauge the usefulness of the design space experiences, where results generally show the high potential of the experiences. Future systems can be developed to utilize consumer-grade HMDs, such as Hololens or Google glass (Google 2019, Microsoft 2019) (as show in Figure 39). These HMDs are equipped with numerous sensors and I/Os, and can function for extended periods of times. Therefore, we will investigate integrating those HMDs for use with weARable within realistic user scenarios.
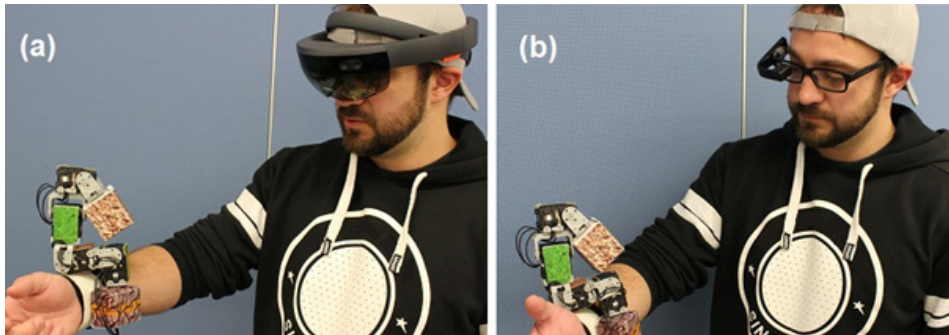
Figure 39 shows additional HMD implementation directions, which utilize consumer grade products. These products provide robust tracking and sensing capabilities, which can further expand the possible experiences of weARable.

The integration-framework and the design space experiences present substantial contributions to realizing serpentine-shaped robotic appendages. The framework is based on a publisher-subscriber model, which allows a variety of I/Os or smart-devices to interface with the wearable robot, thereby making it easier for designers to explore and develop cross-device user experiences. In addition, the design space presents the first efforts to realize user experiences based on the two interaction paradigms extracted from previous works. The developed experiences also reflect initial insights that pointed out the importance of multipurpose use, therefore, the interaction experiences spanned across different domains. Most importantly, weARable provided a manifestation of how multipurpose user experiences can be developed, thereby addressing the main challenge of enabling users to switch between different paradigms or purpose domains. The resulting insights are accordingly analyzed and discussed within section 5.3 User Experience Design.

4.5 HapticSnakes

4.5.1 Introduction

Nowadays, VR plays a large role in delivering immersive experiences for both business and entertainment. Researchers argue that to further enhance immersion in VR, physical interactions with digital contents should be conveyed within VR (Brooks 1999, Hoppe, Knierim et al. 2018). Therefore, haptic feedback has a huge potential in enhancing VR experiences. Moreover, Haptic feedback plays a large role in a variety of experiences, such as an information rich feedback delivery systems or to convey information in novel feedback modalities (He, Xu et al. 2015, Ion, Wang et al. 2015, Luzhnica, Veas et al. 2016, Yamazaki, Mitake et al. 2017, Strasnick, Holz et al. 2018).

Many research in the literatures presented devices that deliver a variety of haptic feedback in VR, such as to feel an object's weight (Choi, Ofek et al. 2018) or tangential or shear forces (Whitmire, Benko et al. 2018). These works mainly focused on the hands or arms, thus deemphasizing other regions of the human body. However, feedback on other regions, such as front and back torso, has high potential in increasing presence and immersion in VR (Tsetserukou 2010, García-Valle, Ferre et al. 2016, Delazio, Nakagaki et al. 2018, García-Valle, Ferre et al. 2018). However, literature concerned with the front or back torso are scarce and limited.

Most haptic wearable devices explicitly provide a single type of feedback (Jones, Nakamura et al. 2004, Konishi, Hanamitsu et al. 2016, Hardlight-VR-Suit 2019). Therefore, users have to wear many devices to receive multiple types of stimuli on various body locations. Multipurpose feedback devices are an emerging direction to address these challenges by

triggering different stimuli, thus yielding higher immersion, enjoyment, or multiple modalities for information transfer (Ion, Wang et al. 2015, Dementyev, Kao et al. 2016, Murakami, Person et al. 2017, Ranasinghe, Jain et al. 2017, Choi, Ofek et al. 2018, Harley, Verni et al. 2018, Ranasinghe, Eason Wai Tung et al. 2018).

To address the above challenges, we present HapticSnakes, which consists of two waist-worn serpentine-shaped robots capable of multiple types of feedbacks. Based on our literature review, HapticSnakes is the first to investigate a wearable snake-morphology for providing novel feedbacks within immersive VR. Therefore, the aim of this case study is to expand our understanding of HapticSnakes's feasibility and potential for enabling novel user experiences.

We implemented two prototypes 1) HapticSerpent (HS), which is light weight and better suited for tapping and gestural feedback. 2) HapticHydra (HH), which is designed for delivering multiple feedback types through its multifunctional end-effector, which includes a gripper, a finger, a brush and a fan. We demonstrate how the versatility of the HapticSnakes enables it to reach different locations when worn in front or back torso, like the chest, abdomen, arms, neck, face, shoulder and back.

We extracted a design space based on our implemented prototypes, comprising different feedback types and control attributes to construct experiences. Accordingly, we conducted two user studies that evaluated our prototypes and the feedback types. Since taps are easy to deliver and useful for conveying a variety of cues, our first evaluation focused on distinguishability of tap locations and strengths on front and back torso. Participants had the highest accuracy in distinguishing feedback on the upper-most regions of the front and back torso and had superior overall accuracy in distinguishing tap strengths over tap locations.

To evaluate HapticSnakes within VR, our second user study investigated our robot's capability of delivering multiple novel feedback in VR, as well as users' impressions of using and wearing our robot. The results indicated that participants had distinct preferences for feedback types and were in favor of using our system throughout. The results also highlighted essential challenges in visuo-haptic mismatch while delivering feedback. Lastly, we extracted design considerations and discussed limitations and future research based on our work. The HapticSnakes project expands our the work conducted on the HapticSerpent (section 4.3 (Al-Sada, Jiang et al. 2018)), through extended robot design, analysis, implementations and evaluations.

In this project, our contributions are the following: 1) The design and implementation of multi-haptic feedback wearable robots. 2) Evaluation results that a) gauge the users' accuracy in distinguishing tap locations and strength on the front and back torso. b) Investigate our robot's ability to deliver multiple novel feedbacks in VR, as well as to investigate users' impressions of receiving novel feedback in VR; including taps, gestures, shear forces, blowing air, brushing user's hand and feeding the user.

4.5.2 Related Works

Our work extends four strands of previous works: 1) Vibrotactile feedback, 2) Gestural feedback, 3) Varied Feedback in VR, and 4) Commercial products. We discuss each of these areas as the following:

Vibrotactile Feedback: Vibrotactile stimulation has been thoroughly investigated in previous literatures. Numerous works presented vibrotactile systems for the torso using vests (Jones, Nakamura et al. 2004, Lindeman, Page et al. 2004, Wu, Fan et al. 2010, Konishi, Hanamitsu et al. 2016). While vibrotactile feedback has a wide array of applications, it remains limited; as vibrations cannot stimulate sensations like shear forces or strong impact (Ion, Wang et al. 2015). Also, feedback is constrained to the area where the vibrotactile motors are

fixed on.

Gestural feedback constitutes tangential and shear forces applied on the skin (Corley 2010, Roudaut, Rau et al. 2013), forming perceivable patterns like swipes or circles. Ion et al. (Ion, Wang et al. 2015) presented arm worn prototypes comprising tractors that can stretch and move along the skin, creating different patterns that can be used to convey information. Je et al (Je, Choi et al. 2017, Je, Rooney et al. 2017) introduced tactoRing, which used circular tractors embedded in a ring to drag the skin around fingers. Works in this domain mainly investigated haptic cues as potentially rich information mediums, where they could supplement interactions with wearable or mobile devices. HapticSnake is different, as it tackles the domain of delivering multiple types of feedback in VR experiences.

Varied Feedback in VR: Researchers have investigated a variety of feedback types, including haptic feedback that aimed at attaining deeper immersion and presence in VR. Different works utilized fans to generate air flow, such as a fixed fan on a head mounted display (Ranasinghe, Jain et al. 2017, Ranasinghe, Eason Wai Tung et al. 2018), multiple fans around user's head (Rietzler, Plaumann et al. 2017) or wrist (Shim, Lee et al. 2018). Strasnick et al. (Strasnick, Cauchard et al. 2017) presented a prototype that includes 6 small wrist mounted brushes, where attributes like rotational speed, duration and direction can be utilized to convey different information. Force jacket (Delazio, Nakagaki et al. 2018) uses inflatable modules that are distributed on the user's torso, arms and back. Their prototype is able to convey different types of feedback by variating inflation speed, frequency or duration at each module. However, similar to vibrotactile motors, inflatable modules are prone to limitations in the diversity of expressible feedbacks and variety of feedback locations.

Eating in VR has also been investigated. Mae and Tuanquin (Tuanquin 2017) explored behavioral changes in eating habits using VR, where they introduced Redirected Eating (RE); which controlled food desirability through olfactory and visual manipulations of real food within VR. Harley et al. (Harley, Verni et al. 2018) explored involving various non-digital and passive sensory stimuli with eating in VR, such as touch, smell among others. Arnold et al. (Arnold 2017) explored eating in VR as a part of a game mechanic, where users had to physically grab and eat food in order to win the game.

Compared to these works, HapticSnakes is proactive; it can manipulate food items (e.g. hand-in a cookie to the user), or directly feed users in VR. These capabilities enable a variety of intriguing VR experiences involving food, such as to tackle eating disorders (Ferrer-Garcia, Gutiérrez-Maldonado et al. 2013, De Carvalho 2017).

Commercial products mainly use vests with embedded vibrotactile motors at varied locations to convey haptic feedback on the front and back torso or arms (Woojer , Hardlight-VR-Suit 2019, Tactile-Navigation-Tools 2019, Tactsuit 2019). ARAIG (ARAIG 2018) uses inflatable bladders to simulate impact or pressure applied to the torso. Therefore, we conclude that most commercial vests offer a single feedback type and exclude novel feedback types.

Compared to previous works and products, the novelty of HapticSnakes is in its multi-feedback capability and flexibility. While previous works proposed wearables with a single feedback method, HapticSnakes is able to deliver a variety of feedbacks using a single wearable robot. Such flexibility enables users to experience different feedback types without being overloaded with multiple wearables or accessories. Lastly, HapticSnakes' flexible design enables it to reach various body locations, thereby making it applicable to a wider domain of experiences.

4.5.3 HapticSnakes

To embody the concept of HapticSnakes, we developed two robots that comprise

wearable appendages with a flexible body. Our robots extend the design of snake robots with a fixed base, enabling them to reach a variety of locations and deliver different feedback types. The two robots are the following:

4.5.3.1   HapticSerpent (HS)

Design Objective: The objective of the HapticSerpent is to be able to deliver taps and gestures in different locations and force magnitudes with the lightest possible weight. The robot can be worn in the front or back torso.

Robot Design: The robot's body comprises six serially connected hobby servomotors as shown in Figure 59 (EZ Robot (EZ-Robot.com 2019)), Stall torque = 1.9 Nm). The servomotors are linked together using plastic brackets, which are light in weight and their formation can be reconfigured to match different body dimensions. The robot is shown in Figure 23

Dimensions and Attachment: The robot weighs 742 g and its total length is 51 cm, both robots are mounted on a base with extended brackets and attached to a multitool vest (Figure 59), weighing 300 g. The vest enables easy wearability, adjustment and fit for a variety of users.

End-Effector: We used a 3D-printed bracket (W=3 cm, H=3 cm, L=6.5 cm) and attached it to the last servo to be used as an end-effector. We chose this end-effector size as it is slightly bigger than a human-finger, which provides a bigger contact surface when applying taps. Also, this end-effector is long enough to enable adjusting its direction when delivering feedback. Other End-effectors with varied dimensions or shapes can also be used, such as softer or sharper end-effectors.

Control and Power: To control the robot, we utilized an EZ-Robot Control-Board (EZ-Robot.com 2019). We designed network-invokable controls on top of the EZ-Builder framework to enable easy creation and playback of movements. We powered the robot using 8 v 1800 mA Li-Po battery (approx. 25 minutes of continuous use).

4.5.3.2   HapticHydra (HH)

Design Objective: The objective of the HapticHydra (HH) is to be able to deliver multiple types of feedback to the user's front and back torso, hands and face.

Robot Design: Similar to the HS, the HH is designed as a snake-like robot, yet the servomotors configuration is slightly altered (Figure 40). The three servomotors of the base are of type Robotis MX64AT (Robotis 2019) (Stall torque = 5.5 Nm), which were selected for their high torque and PID control capabilities. The upper three servomotors are of type Robotis AX12A Stall torque = 1.5 Nm), which are used to position the end-effectors for applying feedback.
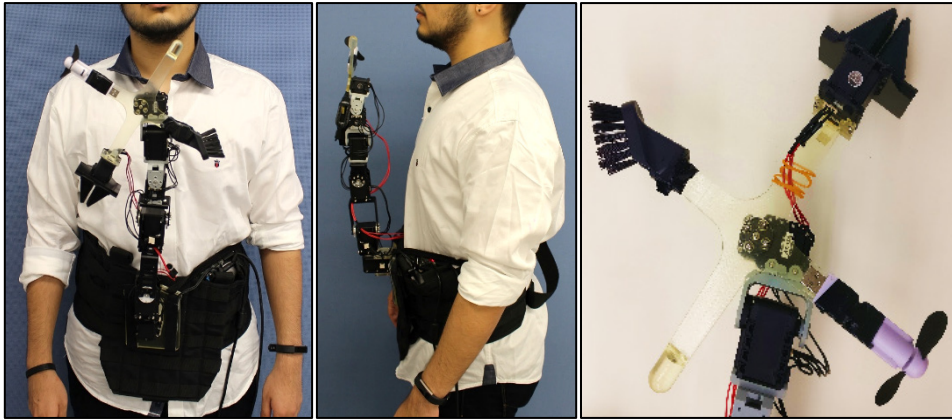
Figure 40 Front, side views of HapticHydra. The multifunctional end-effector is able to deliver multiple types of feedback as it is equipped with a gripper, a fan, a finger-shaped effector and a brush.

The lower brackets connecting the stronger servos are made from aluminum, while the upper ones are made from plastic. This structure minimizes flexing and vibrations that may occur during rapid robot movements. We used servomotors as they provide a good tradeoff between power and weight for our intended applications, enabling the robot to withstand the weight of the end-effector and deliver the intended feedbacks.

The Design of the Multifunctional End-Effector: the HH's end-effector is optimized to offer multiple feedback types; it enables easy selection and delivery of varied feedbacks while being light weight. Other end-effectors, such as anthropomorphic robotic hands, are limited in their feedback variety (e.g. they are unable to deliver airflow or tickling stimuli). Moreover, robotic hands are complex in structure; they are relatively heavy (e.g. Allegro Hand weighs 1.8 kg (Allegro-Hand 2019)) and require sophisticated controls of the hand pose and finger locations to deliver feedbacks. In comparison, the HH's multifunctional end-effector is superior in feedback variety, control over the type of delivered feedback and its associated attributes, while also being light weight.

The rotary end-effector (Figure 40) is able to deliver a variety of stimulations and experiences. It is comprised of a plus shaped 3D printed structure, with a different end-effector type at each of its ends. This structure enables us to easily switch between four different types of feedback by simply rotating the whole structure. We equipped each side with a different end-effector type; a brush, a gripper (Trossen-Robotics 2019), a fan and a finger as shown in Figure 40. By controlling the robot arm's posture, we can control various feedback attributes, like the location and frequency of feedback, as well as the amount of exerted forces and angle of contact when delivering haptic feedback.

Dimensions and Attachment: The robot weighs 1.5 kg and is 42 cm in length (Measured from the robot's base). The rotary end-effector weighs 150.8 g, 18 cm in width, 17.8 cm in length and 0.5 cm in height. The finger-shaped end-effector has a radius of 1.6 cm. We used the same vest from the HS to attach the HH using a custom 3D printed bracket fastened using straps.

Control and Power: We extended the Robotis SDK (Robotis 2019) to customize and integrate our controls. Our control software allows us to create and playback movements and motions through direct teaching (i.e. physically moving the robot to the desired pose). Motions can be played with varied attributes, such as varied playback speeds or joint angles. Moreover, we created a websockets network interface (Websocket.org 2019) with all robot commands, so that they can be easily invoked from VR environments. Our software was designed this way to enable rapid prototyping, experimentation and easy integration with

different systems. The control software runs on a GPD win mini PC (GPD). To power our system, we used a 12v 1800 mA Li-Po battery that can provide approx. 20 minutes of continuous use of the robots.

4.5.4 HapticSnakes Design Space

In order to study different feedback types in HapticSnakes, we analyzed the robots formfactor, workspace and end-effectors. Then, we juxtaposed the extracted feedback types with robot control attributes, such as speed, applied torques and motion. Accordingly, we extracted a number of dimensions for designing experiences (as shown in Figure 61), and they are presented within the next subsections.
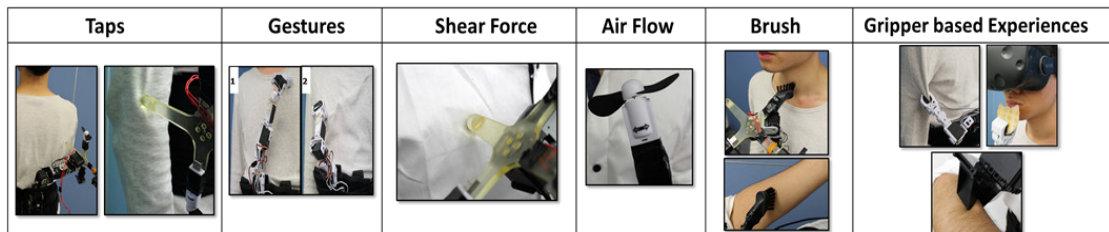
Figure 41 Design Space of HapticSnakes. Each design dimension corresponds to a specific feedback category and include specific attributes.

4.5.4.1 *Feedback and Attributes*

A. *Taps*

Taps resemble a force applied to a specific area for a brief amount of time. Taps are versatile and may be used to convey a variety of visual stimuli, events or notifications.

Design Attributes: Location constitutes where the feedback is delivered, which is applicable to all feedback types. When mounted on user's front waist, HapticSnakes reachable workspace include the user's face, neck, torso, shoulders, arms and hands. When mounted on the back torso, reachable areas are the back torso, back of the neck, shoulders, arms, hands and head. *Strength* resembles the amount of applied force on impact, while *direction* represents the angle of applied with respect to target area.

B. *Gestures*

Gestures allow for prolonged forces to be applied to the body at varied locations and directions, creating shapes like a circle, zigzag or a swipe. HapticSnakes is able to apply gestures both on users' worn clothes or skin.

Design Attributes: In addition to *Location*, *Strength* determines the applied force on the user's body. *Duration* represents the time required to complete one gesture, while *Trajectory* corresponds to the sequence of movement path for creating the gesture.

C. *Shear Forces*

Shear Forces are carried out by continuously applying a force against a specific body region. They are useful in representing physical interactions like nudging, poking, or objects that are stuck to the user's body.

Design Attributes: Location attributes are applicable (as explained in taps). *Strength* resembles how much pressure is applied on the user's body, while *direction* resembles the angle of applied force with respect to the application area. *Duration* determines how long the shear force is applied.

D. *Airflow*

The mounted fan is able to generate an airflow in different body regions, which is essential for increasing immersion (Ranasinghe, Jain et al. 2017, Rietzler, Plaumann et al. 2017,

Ranasinghe, Eason Wai Tung et al. 2018). Unlike previous systems which focused on the face, HapticSnakes can deliver such feedback to other locations. For example, an airflow can target the neck or hands if a hand-tracking system is used.

Design Attributes: Besides *Location*, *Intensity* corresponds to amount of blown air on the user, which can be controlled either by the fan speed or distance between the fan and target area. *Direction* corresponds to the angle of the fan with respect to the target area. For example, a fan facing the user may blow air facing upward or downward, such that the air flow can be felt coming from under the chin or above the nose.

E. *Brush*

Brushing on the user's skin can generate a variety of tactile sensations, from tickling to scratching. Such feedback can be paired with a variety of visual stimuli, such as to resemble touching hair or fur.

Design Attributes: In addition to *location*, brushing has unique attributes. *Intensity* refers to how much force is applied on the users' skin, less *intensity* resembles a gentle experience like tickling, and higher ones convey an immense sensation similar to scratching. *Trajectory* comprise the path taken during brushing, and *Speed* determines how fast the brush travels along a path.

F. *Gripper Based Feedback*

This category covers several experiences that are delivered using the gripper. First, pinching the user's skin at different locations. Second, manipulating objects, such as handing in objects to users or feeding them. Lastly, pulling the user's clothes.

Design Attributes: In addition to *location, Strength* resembles the magnitude of the pulling-force applied on user's cloths, or strength of pinching the skin. *Speed* resembles how fast the pinch is carried out or how fast the clothes are pulled. *Direction* determines the angle of pulling clothes.

4.5.4.2 *Designing Experiences*

Designers can convey a variety of experiences by selecting different feedback types and attributes from the design space. Complex experiences can be created by sequencing feedback with different attributes. For instance, repeating a tap twice on the shoulder may resemble being patted by a virtual character.

Feedback can be designed to match various interactions with applications, whether in VR or not. We demonstrate how we utilized the design space to construct experiences for delivering feedback in each of the user studies.

4.5.4.3 *Discussion and Limitations*

The applicability and quality of experiences mainly depend on the robots' design factors, specifications and controls. To optimize the robots' design for specific feedback types, the design space dimensions, and attributes of a desired experience should be expressed as robot design parameters; thereby determining adequate mechanical designs, end-effectors types and level of control over the feedback attributes. Similarly, delivering feedbacks with specific attributes require expressing them as robotic control parameters, such as servomotor speeds, angles, applied torques and robot poses. Therefore, transforming the design space's feedback types and attributes to robotic parameters is essential for both optimizing the robot's design and ensuring accurate feedback delivery.

There are further attributes that may affect the experiences which cannot be implemented without significant enhancements to our robots' hardware or controls. For example, *acceleration*, like applying shear force or gestures with increasing speeds, or *variant*

intensity, like applying a gesture with gradually increased strength. These factors require further optimizations to the robot's mechanical design, control, and accurate tracking of the user's body.

Attributes like feedback strength and intensity are subjective dimensions; a tap that is considered painful by a user could be perceived as weak by another. These individual differences among users should be considered while designing each experience.

4.5.5 Evaluation 1: Distinguishing Taps on the Front and Back Torso

4.5.5.1 Study Design

Taps present a versatile haptic feedback medium. They can be easily delivered with basic mechanical designs, varied attribute, and can be used to resemble a wide variety of VR events (e.g. bumping into objects or being poked by virtual entities). However, related works are scarce for novel haptic cues in general, and especially taps applied on the front and back torso. Therefore, this study aims at broadening our understanding of applying taps as general haptic cues.

Objective: The main objective of our study is to investigate user's capability to distinguish the intensity and location of taps applied to the front and back torso. We accordingly utilized our design space attributes to determine a tap's *location* and *strength* for our study.

4.5.5.2 Calibration of Tap Strengths and Locations

Feedback Regions: Segmentation strategies of the feedback regions on the front and back torso are varied in previous works. For example, Jones et al (Jones, Nakamura et al. 2004) stimulated 9 points on the lower abdomen and back, while Yang et al (Yang, Jang et al. 2002) used a total of 60 vibrotactile motors surrounding the torso (approx. 20 for each the front and back torso). Some previous works also chose different location arrangements based on their evaluation objectives. For example, to evaluate social acceptability of pinching and rolling to interact with smart garments (Karrer, Wittenhagen et al. 2011), which used six feedback points on the torso. Another study (Wagner, Nancel et al. 2013) separated the front torso to six regions to evaluate on body-touch interactions.

Our evaluation objective is to explore the potential of delivering taps to the front and back torso. To the best of our knowledge, no previous work has investigated this type of feedback using this form of robots. Therefore, we build upon the model proposed by Karrer et al. (Karrer, Wittenhagen et al. 2011), that had the closest evaluation objective and feedback locations to our evaluation, by splitting larger regions to smaller ones, and introducing two more extra regions on the chest (which were excluded from Karrer et al's work due to social unsuitability for their interaction method). Since our robots can accurately tap smaller regions, we decreased the sizes of the feedback regions in a similar way to what have been used in haptic vests (e.g. (Jones, Nakamura et al. 2004)). Therefore, we introduced a total of 16 regions (Cells) on each of the front and the back torso.

The 16 cells (Figure 43) have a vertical spacing of 5 to 8 cm that depends on each participant's chest and back size. These spaces are also used to compensate potential operational errors, such as slight robot misalignments that may occur from continuous or rapid robot movements.

Location Calibration: Cells 1 through 4 are aligned horizontally to four points on the collarbone and shoulders for the front torso, and inner and outer edges of the shoulder bones for the back torso. As previously mentioned, the remaining 12 cells are aligned with 5 to 8 cm vertical spacing. On the back, the cells were slightly shifted to the edges to avoid hitting the neck or spinal cord. Our robot was calibrated to tap the user's body in each point, taking into

consideration dimensional differences between each users' body, as well as anatomical differences between males and females.

Strength Calibration: The robot was calibrated to tap the center of each cell from an approximate distance of 8 cm. This distance was chosen as the noise generated by servomotors from this distance at different speeds was undistinguishable, therefore, nullify its potential effect. Next, the strength was determined subjectively by participants; servomotor speeds were continuously adjusted, within a specific range of servo motor speeds for each of the strengths, until the difference between strong and weak taps was easily distinguishable by each participant. We have chosen subjective strong and weak feedback values to accommodate variations in users' clothes that may affect sensed feedback (e.g. a thick shirt, or multiple layers of clothes).

The calibration process was repeated for each cell, covering both weak and strong feedbacks. To ensure applying sufficient force, strong and weak taps were tested and verified by users after calibrating each cell and before moving on to the next cell. For safety, we adjusted the servos speeds between 5~10 rpm for weak taps, and 20~25 rpm for strong taps. The calibration process took approx. 50 minutes per user.

We tested the amount of exerted forces when applying taps with specified speeds using a force sensor (Appendix 3). Using the HS for the front torso, the exerted forces are approx. 2.93 N for weak taps, and 5.31 N for strong taps. Using the HH for the back torso, the exerted forces are approx. 3.30 N for weak taps, and 7.40 N for strong taps. Despite using the same servo speeds, the HH had a slightly higher amount of applied forces due to its weight and momentum when applying taps.

Participants: We hired 20 college students (Age m=22.80, SD=2.94, 11 Females). They were distributed evenly in two groups (6 females in front torso group). Participants came from different backgrounds, and all participants had a prior knowledge of VR through research or commercial platforms.
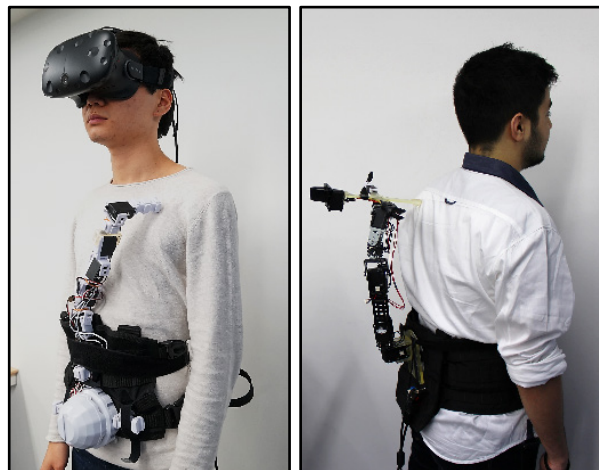
Figure 42 User study conditions. The HS and HH were respectively used for taps in front and back torso

Procedure: The user study was carried out in the same manner for both the front and back torso (Figure 42). We started with an introduction to our work and the robots, followed by a profiling questionnaire. Next, we carried out the calibration processes as described. Next, participants took a familiarization tutorial, which included a single dry run of weak and strong taps for each of the 16 calibrated cells. The trials phase started by first blindfolding the participants then subjecting them to feedback on the 16 cells. After each tap, participants had to verbally indicate the cell number and strength of the felt tap. Similar to the procedures of

previous related studies (e.g. (Wilson, Carter et al. 2014, Luzhnica, Veas et al. 2016, Gil, Son et al. 2018)), we randomized and repeated the trials three times on each cell and strength level to minimize potential feedback errors and learning effects. Therefore, each participant was subjected to 96 taps (16 cells x 2 strengths x 3 repetitions). We have also monitored the robot's position and feedback delivery for potential errors throughout the user study. After the study, participants took a 5-point Likert scale usability questionnaire (1 is Disagree/Bad, 5 is Agree/Good), based on the Questionnaire for User Interaction Satisfaction (QUIS) (Chin, Diehl et al. 1988). Lastly, each participant had a semi-structured interview covering aspects of usability and wearability. Each user study lasted approx. 2 hours.

4.5.5.3   Results and Analysis

In this section, we analyze the accuracies gathered from different conditions (Figure 43). We start by highlighting our main analysis objectives, followed by the analysis results and discussion. Accuracy of Distinguishing Taps We focused our investigation on exploring three main aspects of participants' accuracies that we believe are essential for designing feedback for future experiences: *Q1*: Whether the accuracies in upper regions is higher than lower regions. Since we used a within-subjects study design for each front and back torso, we used a repeated measures ANOVA that compared rows 1, 2, 3 and 4 in each condition to validate our objective.*Q2*: Whether or not the accuracies were higher in the chest than the abdomen on the front torso, and shoulder-blades than lower-back on the back torso. To form mentioned regions, we combined rows 1 and 2 to form the chest region and rows 3 and 4 to form the abdomen region on the front torso. Similarly, we combined rows 1 and 2 to form shoulder-blades region, and rows 3 and 4 to form the lower-back region on the back torso. We compared the results on the front and back torso separately, and we used paired-sample t-tests due to our within subject user study design.
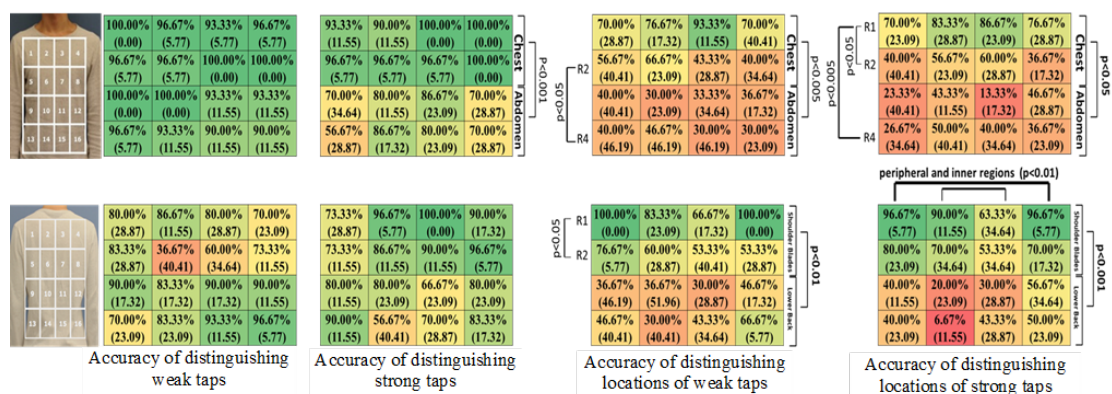
Figure 43 Calibration cells, average accuracy of distinguishing feedback strengths and locations at each cell location for all participants (Standard Deviation values in brackets). Results of the statistical significance tests on various regions are also illustrated (discussed the results section)

Q3: Whether the accuracies were higher in peripheral regions than in inner regions. We investigated this aspect as previous works suggested a potential difference in accuracies among peripheral and inner regions (Jones, Nakamura et al. 2004). We formed peripheral regions by combining columns 1 and 4 (as shown in feedback matrix of Figure 43) and inner regions by combining columns 2 and 3. We used paired-sample t-tests to compare accuracies across these regions within each the front and back torso.

The following subsections examine each of the questions within the conditions of our user study.

4.5.6   Analysis of Taps on the Front Torso

Distinguishing Locations of Strong and Weak Taps: *Q1:* we conducted a repeated measures ANOVA between the four rows, which showed that the accuracies statistically differed for strong taps, using Greenhouse-Geisser correction (F(1.10,3.29)=16.81, p<0.005) and weak taps (F(3,9)=16.83, p<0.001). In strong taps, post-hoc tests using the Bonferroni correction showed significant difference between rows 1 and 2 (p<0.05), rows 1 and 4 (p<0.005), which indicate a generally higher accuracy in row 1 in comparison to other rows. In weak taps, a similar procedure was repeated, which only showed significant difference between rows 2 and 4 (p<0.05).

Q2: we used a paired sample t-test to compare the accuracies of the chest and abdomen regions, which showed a significant difference in strong taps (t(7)=3.37, p<0.05) and in weak taps (t(7)=4.66, p<0.005). These results indicate that participants' accuracy of distinguishing feedback on the chest were generally higher than the abdomen region. To address *Q3*, our tests did not show significant differences in accuracy between inner and peripheral regions.

Distinguishing Tap Strengths: Q1: repeated measures ANOVA results showed a significant difference in distinguishing accuracies of strong taps (F(3,9)=11.70, p<0.005). However, pair-wise comparisons did not show significant differences between regions, likely because of the limited sample size and used correction method (see discussion). *Q2*: accuracies on the chest and abdomen were only statistically different for strong taps (t(7)=5.58,p<0.001). Significant differences were not observed in the evaluation of *Q3*.

Qualitative Analysis: Participants rated *"I can easily distinguish the feedback location among different cells"* with 2.5 (SD=0.85) and *"I can distinguish feedback location among contiguous cells"* with 2.70 (SD=0.95). Several participants also indicated that identifying feedback on the edges of the torso is easier than the center, yet statistical analysis did not reveal a significant difference. As shown in Figure 43, both strong and weak taps were easily distinguishable by users, even when participants could not accurately distinguish the location of taps. Participants rated the ease of distinguishing tap strengths with 3.40 (SD=1.07). Participants rated "Did the taps feel painful?" with 1.70 (0.82) and did not report any specifically painful feedback cells.

4.5.6.1   *Analysis of Taps on the Back Torso*

Distinguishing Locations of Strong and Weak Taps: *Q1*: repeated measures ANOVA showed significant differences in distinguishing strong tap locations (F(3,9)=15.53, p<0.001) and weak tap locations (F(3,9)=17.70,p<0.001). Post-hoc tests using the Bonferroni correction did not yield significant differences between accuracies of strong taps, while weak taps had a significant effect between rows 1 and 2 (p<0.05). Similar to the front torso, we believe a larger sample could have yielded significant results in pair-wise comparisons.

Q2: paired t-test results indicate higher accuracies for shoulder-blades than lower-back in both strong taps (t(7)=5.65,p<0.001), and weak taps (t(7)=3.696,p<0.05). *Q3:* The accuracy of distinguishing feedback on peripheral regions were found to be higher than inner regions in strong taps (t(7)=4.89,p<0.01), while weak taps did not show any significant difference. Therefore, we conclude that distinguishing tap locations had higher accuracies in upper regions than in lower regions of the back torso.

Distinguishing Tap Strengths: similar to our previous analysis, we carried out a repeated measures ANOVA for *Q1*, followed by a paired sample t-test to compare the accuracies on the shoulder-blades and lower back (*Q2*), and a paired t-test to validate accuracies on inner and peripheral regions (*Q3*). As expected, no statistical difference could be observed in all tests as the accuracies were generally high across all cells (strong taps

m=82.08, SD=11.98, weak taps *m*=79.17, SD=14.93).

Qualitative Analysis: overall, we believe participants thought it was difficult to distinguish the feedback locations. Participants rated *"I can easily distinguish the taps applied on different cells"* with 2.50 (SD=1.08) and *"I can distinguish feedback between contiguous cells"* with 2.30 (SD=1.06). In contrary, participants rated their ease of distinguishing feedback strengths with 2.90 (SD=1.10), which further confirms the high accuracies and our analysis results of distinguishing feedback strengths. Although participants generally thought the feedback was not painful (*m*=2.30, SD=1.25), the interviews revealed that some participants thought that some feedback areas were painful; Three participants specifically indicated that cells 6 and 7, located right above the scapula of the shoulder bone, felt painful and should be avoided.

4.5.7   Overall Analysis

4.5.7.1   *Distinguishing Taps on Front and Back Torso*

Distinguishing Tap Locations: On the front torso, the overall accuracy of distinguishing the locations of weak taps is (*m*=50.21%, SD=19.53) and strong taps is (*m*=49.37%, SD=20.90). On the back torso, the overall accuracy of distinguishing the locations of weak taps is (m=58.13%, SD=22.6) and strong taps is (m=56.70%, SD=26.58).These results indicate that the overall accuracy of distinguishing tap locations is not very high, yet participants had significantly high accuracy in upper regions of the front and back torso (as indicated in section 5.2.1).

We compared strong and weak feedback separately on each the front and back torso, with the goal of identifying which of condition had a significantly high accuracy. While there was not a difference on the front torso, paired-sample t-tests on the back torso conditions showed that weak tap locations were more distinguishable than strong tap locations on the back torso (t(15)=2.67,p<0.05).

Moreover, to identify regions with significantly high accuracies, we compared the overall accuracies in distinguishing strong and weak tap location between the front and back torso. We conducted a one-way ANOVA with Bonferroni correction, which compared all the four conditions of distinguishing tap locations on front and back torso. Results did not show a significant difference in the accuracy within a specific condition; therefore, we conclude that users had a similar accuracy in distinguishing tap locations across different conditions.

Distinguishing Tap Strengths: Users had an overall high accuracy in distinguishing tap strengths on front and back torso. On the front torso, their overall accuracy in distinguishing strong taps is (m=85.83%, SD=13.42) and weak taps is (*m*=96.04%, SD=3.49). On the back torso, overall accuracy of distinguishing strong taps (m=82.1%, SD=11.98), and weak taps (*m*=79.17%, SD=14.93).

To compare the different conditions, we carried out a one-way ANOVA with Bonferroni correction that compared the four conditions of distinguishing tap strengths in front and back torso. Results showed significant difference (F(3,60)=29.36,p<0.001). Pair-wise comparisons showed significant differences between distinguishing strong taps on front torso and strong taps on the back torso (p<0.05), and strong taps on front torso and weak taps on the back torso (p<0.001), indicating a higher distinguishability of strong taps on the front torso than mentioned conditions. Weak taps were also found to be more distinguishable on the front torso than weak taps on the back torso (p<0.001), but no significant difference was found between weak taps on the front torso and strong taps on the back torso. Therefore, we conclude that tap strengths were generally more distinguishable on the front torso than on the back torso.

We believe that these results justify the limited findings of our statistical analysis; as there were not many significant differences among the cells because the accuracies were generally high.

Tap Locations and Strengths: we compared the overall accuracies of distinguishing tap locations with tap strengths across both the front torso and back torso. We used paired-sample t-tests to compare the overall accuracies of locations with strengths, separately on each the front and back torso. Participants had superior accuracy in distinguishing tap strengths over locations, in both front torso (t(31)=12.40, p<0.0001) and back torso (t(31)=5.07, p<0.0001). We discuss the impact of these results in the Design Considerations section.

4.5.7.2   Male and Female Accuracy Analysis

We analyzed the accuracies for both front and back torso conditions for males and females. Since the number of males and females is unbalanced in the front torso condition (6 females and 4 males), we used Welch's t test. Females (m=56.94%, SD=36.16) significantly outperformed males (m=40.10%, SD=33.69) in their overall accuracy of distinguishing the locations of weak taps on the front torso (t(142)=3.007, p<0.05, Cohen's d= -0.481). Similarly, a significant effect was found in overall females accuracy (m=56.60%, SD=34.58) compared to males (m=38.54%,SD=40.37) in distinguishing the locations of strong taps on the front torso (t(120)=2.93, p<0.05, Cohen's d=0.480).

We analyzed the results on the back torso under the same conditions and using the same statistical test, yet results did not show significant differences (Appendix 4 contains further results). We further discuss these results within the Discussion and Limitations section.

4.5.8   User Satisfaction, Comfort and Fit

Participants rated their overall satisfaction with the HS with 3.80 (SD=0.92) and the HH with 3.00 (SD=0.0). Generally, they really liked the idea of feeling the taps at different intensities and in different locations and thought it could make a very novel VR experience.

Participants rated the comfort of the HS with 3.80 (SD=0.79) and weight with 3.70 (SD=0.95), while the HH was rated with 2.70 (SD=1.34) for comfort and 3.10 (SD=1.10) for weight. Although both the HS and the HH had close ratings for weight, we conclude that the overall perceived comfort was better for the HS, as it's' smaller size and lighter weight enabled it to be more comfortable throughout the study. Participants also thought that both robots should be lighter in weight, so that they can be worn for prolonged periods of time.

4.5.9   Discussion and Limitations

The results of our analysis on distinguishability of taps on different regions indicate that the accuracies were higher in the upper regions of the front and back torso. We attribute the high accuracies on upper regions to closeness to the collar and shoulder bones on the front torso, and shoulder-blades on the back torso. Apart from strong taps applied to the back torso, results also showed that feedback was not significantly distinguishable in inner or peripheral regions. Therefore, we conclude that participants had a similar overall accuracy in distinguishing feedback in inner and peripheral regions.

The overall analysis also showed interesting aspects. The overall accuracies of distinguishing tap locations were not very high, and we conclude that participants had similar accuracies across all conditions. The results also point out that despite the overall high accuracy in distinguishing tap strengths, participants had significantly higher accuracies in the front torso than on the back torso. Lastly, the overall distinguishability of different tap strengths is significantly higher than tap locations, both on the front and back torso. Therefore, we believe these findings can be utilized to optimize tap delivery within different

experiences. For example, delivering more precise taps on the upper regions than lower ones. We discuss essential implications for designing future experiences within the Design Considerations section.

The accuracy comparisons between males and females also revealed interesting insights. There was a statistical difference in distinguishing the locations of strong and weak taps on the front torso, where females had significantly higher accuracy. We attribute these results to anatomical differences between males and females on the front torso area, which contributed to higher female accuracy in distinguishing tap locations. We believe future systems should accommodate these anatomical differences during the calibration process, and also adapt user experiences to exploit such differences (e.g. an experience with a female participant could apply taps across many cell locations, and vice versa for males).

Another essential factor is the size of the users' torso when using the HapticSnakes. We believe the width of the users' front and back torso affected feedback accuracy. Users with larger bodies had sufficient distance between cells, which we believe have increased their distinguishability of feedback on different regions, and vice versa. Future systems should attempt to compensate such variance in the users' torso sizes.

In order to maintain safety and meet our evaluation objectives, we limited servo speeds and the amount of exerted forces in this study. The robots are capable of exerting much higher and lower amount of forces, such as by increasing or decreasing the servomotor speeds. Therefore, future work should investigate the effect of exerting varied amount of forces, thoroughly investigating the full spectrum of possible applied forces on different body regions.

Lastly, we believe some of our statistical analysis results were slightly affected because of the correction used (Type 2 errors). These tests may also indicate the need for a larger sample to show significant difference among users' accuracies.

4.5.10 Evaluation 2: Investigating HH's Novel Feedbacks in VR

4.5.10.1 Study Design

The scarcity of studies about multi-haptic feedback devices motivated us to investigate the HH's usability and potential for use in VR. The novelty of the HH is in its ability to deliver multiple types of novel feedback in VR. Previous works on novel haptic feedback wearables focused their evaluations on validating the capabilities of their designs in delivering novel feedbacks (Maimani and Roudaut 2017, Delazio, Nakagaki et al. 2018). Therefore, we focused our study on investigating the unique capability of the HH in delivering multiple novel feedback types, and therefore contributing with design insights, potential challenges and limitations of robots based on the HH.

Objectives: The main objectives of this study are to 1) Investigate the HH's capability to deliver multiple feedbacks in VR, and to 2) explore users' impressions about using the HH and experiencing its novel feedbacks in VR. Accordingly, we evaluated taps, swipes, shear forces, brushing against skin, blowing air and feeding, where each was matched with visual and auditory stimuli.

4.5.10.2 Participants and Apparatus

We hired 10 college students, aged between 19 and 31 (*m*=24, all males), who came from different disciplines and eight nationalities. Six participants indicated that they have experienced VR before, and non-had prior experiences of haptic feedback in VR.

Our experience was fully developed with the Unity3D (Unity3D 2019). We ran the experience on a computer connected to an HTC Vive head mounted display (HTC Vive) with

headphones (as shown in Figure 44).

Our Unity3D software communicates with the HH using WebSockets (Websocket.org 2019). As described in the HH implementation, robot control commands are sent from our software to trigger each robot movements and feedback delivery in synchronization with the visual and auditory stimuli running in our experience.

Figure 44 1) User study conditions and hardware. We utilized HTC Vive to deliver our VR experience. Two PCs were used, one for running Unity3D/VR experience, and the other to control the robot. 2) The VR environment involves several experiences with changing weather, ambient effects and day/night cycles.

4.5.10.3 Experiences and Story

We developed an immersive VR experience with a story, visual and auditory effects to match HH's delivered stimuli. The story is about a person enduring a nightmare consisting of 7 experiences that are shown and explained in Figure 45. These experiences are not interactive, and their flow is predetermined. Each experience lasts for around 20-30 seconds. Varied environmental, atmospheric and sound effects were added in each experience, therefore contributing to the overall immersion and flow of experiences (Sheridan 1992, McMahan 2003, Ekman 2013).

4.5.10.4 Feedback Calibration

We instructed users to stand straight and maintain their pose for the calibration. We used the design attributes of our design space to calibrate each experience. To ensure safety and to ease calibration, the direction was fixed for all feedback to be perpendicular to the user's body, and the maximum strengths were fixed with a servo speed of 25 rpm, from a distance of approx. 8 cm (Similar to the previous study). Calibration took 25 minutes per user, and consisted of seven calibration processes for each of the seven experiences:

1. *Cat Rub:* brushing was carried out on the user's left forearm, where we applied 2 swipes against the user's skin with a length of 3 cm and a speed of 10 rpm. These attributes were chosen as they mimic the cat rubbing itself on user's arm in VR, and brushing was repeated twice to enable users to experience brushing as a single swipe could be too short to feel.

2. *Patting*: To resemble gentle pats on the user's shoulders, the finger end-effector was moved towards the user's shoulder at a *speed* of 10 rpm from a distance of 5 cm. This movement was executed twice, where the robot briefly rested against the users' shoulder in between actions to match the VR experience. *3. Knight Slashing*: we calibrated the end-effector on the surfaces of cells 2 and 3 centers. The angle of the base servomotor was increased by approx. 5º to generate a force for a *length* of 12 cm, a *speed* of 10 rpm and in a straight *trajectory* between the cells, therefore, applying an approximate force of 3.63 N. We chose these cells as the upper chest has a semi-flat area and high sensitivity (as explained in Evaluation 1), enabling us to execute the swipe easier than in other areas. The feedback attributes were chosen to match the sword slash in the VR.

Figure 45 after welcoming the user, the experiences start: 1) a cat comes and rubs her body against the users' left forearm while meowing. Next 2) a character approaches the user and pats his/her right shoulder twice, saying "you are tired, you should go to sleep". Then, the screen fades to black and the user is taken to a scene where it is dark and raining, with matching thunder and rain sounds. The screenshots were taken without ambient effects for clarity. 3) An archer appears in front of the user and shoots an arrow to the user's chest, then disappears into the darkness. 4) A knight appears and slashes user with his sword, then backs away and disappears. 5) A brawler appears and punches the user in the chest, 6) sending them flying into the sky. 7) The user is awoken from the dream, and he/she is fed a cookie.

4. Arrow: a shear force was applied to cell 4 on the chest. Upon position-calibration, the angle of the base servomotor was increased by 10º to apply a *force* for a *duration* of approx. 4 second. The angle was increased by mentioned amount to create a shear force against the user's torso that resembled the arrow in VR. *5. Punch* was calibrated by moving the robot at the *speed* of 25 rpm and distance of 8 cm from the area between cell 2 and 3, matching where the character punches the user in VR. Similar to our previous evaluation, we chose 25 rpm so that we achieve the highest impact force while maintaining

Overall operational safety of the robot. *6. Flying:* a fan was positioned 15 cm away in front of the users face and was manually controlled. The fan is situated so that it blows air on the lower side of the user's face, since the upper side is occluded by the Head Mounted Display. *7. Feeding* was done by moving the gripper to be approx. 6 cm away from the mouth. Such length is chosen to both match the VR character's hands and to enable users to easily lean forward and eat the cookie.

Stimuli Synchronization: To match visual stimuli in VR and HH's delivered stimuli, we compensated the robot movements by calling them ahead of each visual stimulus. This was achieved by observing the robot's movements and compensating them manually on the VR system. We also used a dedicated network router to minimize any effect of network latency.

4.5.10.5 Procedure

First, users were briefed about the purpose of the user study and the system. Then, all participants had a 5-minute simple trial of HTC Vive, after which we carried out the calibration as described. Next, the user study is started as explained in the Experiences and Story subsection, after which participants took a post-study questionnaire and were interviewed. We also adapted QUIS (Chin, Diehl et al. 1988) to this study and extended it with questions about users' impression of each of the experiences. Each trial lasted for approx. 90 minutes.

4.5.11 Analysis of Experiences Preferences

We asked participants to rate how much they liked each experience (5-point Likert scale, 5 is best). Participants rated *flying* (m=5, SD=0.0), *cat rubbing* (m=4.2, SD=0.91), *knight slashing* (m=4, SD=0.94), *feeding* (m=4.4, SD=0.70), *patting* (m=4.2, SD=1.14), *punch* (m=3.9, SD=1.19) and *arrow* (m=3.9, SD=1.20). These results indicate that the experiences were generally enjoyable.

We also asked the participants to rank the experiences quality and enjoyment by comparing the experiences with each other. We used a 7-point Likert scale (7 is best), where each experience could be allocated one unique rank. Ranking the experiences would enable us to extract insights about users' individual preferences. The ranks and their distributions are shown in Figure 46.

To analyze the ranking, we ran non-parametric Friedman test, which showed significant differences in the distribution of the experience's ranks (χ^2 (2)= 14.31, p<0.05). We followed with Wilcoxon signed ranks test with Bonferroni correction, which only revealed significant difference between Flying-Patting only (Z =-3.400, p<0.001). Apart from Flying-Patting, the results indicate that the distribution of the experiences-ranks were generally the same. Therefore, we conclude that participants generally had distinct preferences of the experiences and were not statistically biased towards a certain experience.

4.5.11.1 Qualitative Analysis

We analyzed each experience by evaluating its overall score and qualitative user feedback. We believe such analysis would provide deeper insights about individual preferences about each experience. We examine each of the experiences and report its overall rank score, which is calculated by summing all the participants-allocated sub-scores, as follows:

1- Flying (Overall Rank Score: 59): Eight participants ranked this experience in their top 3. One participant mentioned "*The effect of air blowing was very appropriate; it wasn't too much or too little*", another added "*…it was very realistic, it felt like I was really flying away*". Also, they indicated that auditory, visual and haptic stimuli were consistent, hence calling it realistic. Therefore, we believe the experience was very enjoyable.

2- Knight Slashing (Overall Rank Score: 43): Five participants ranked this experience within their top 3. Some participants mentioned "*…it was most realistic because the whole slash was carried out*" and "*it was intuitive, the timing was good and the motion on the chest was intense.*". This feedback indicates that the visual stimuli and slashing gesture on the body were well received. However, some participants thought that the slashing gesture should be stronger so that it is more consistent with the visual stimulus of slashing.
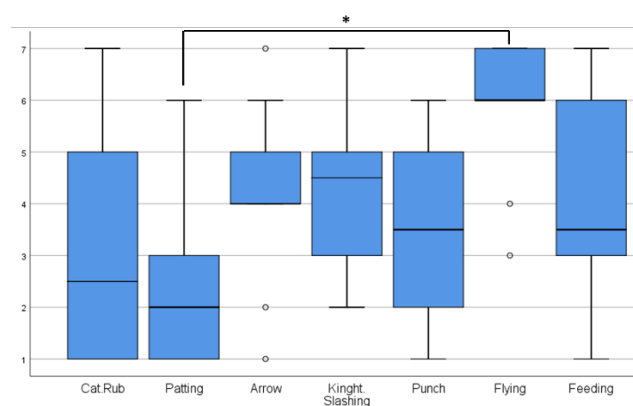
Figure 46 shows the distribution of the experiences as well as the mean rank (Error bars represent 95% CI). Rankings were significantly different for Flying-Patting.

3- Arrow (Overall Rank Score:42): Four participants ranked this experience within their top 3. Participants mentioned: "*I felt the arrow hit and stuck to my body*", "*the whole arrow effect felt realistic, the animation, timing and hit was believable*", which indicate that the experience was both enjoyable and consistent. However, some participants discussed some shortcomings. They thought the arrow's animation should be faster, and proposed increasing

the feedback strength both for impact and when pressing against their bodies.

4- Feeding (*Overall Rank Score:* 42): Although four participants ranked it among their top 3, participants expressed mixed views about this experience. Some participants thought it was very novel and enjoyable, a participant mentioned "feeding is the most realistic experience, because get to taste the food in VR". Another added "It was good, eating the cookie was easy".

In contrary, other participants mentioned some challenges: *"I had to bend a little for eating the cookie"*, *"The cookie hit my chin when I tried eat it".* These comments highlight the issue of correctly aligning the cookie both in VR and real world, so it would be easier to eat. A number of issues effected this experience, especially robot shaking in accordance to user's movements, and the harness loosening upon extended use. Lastly, one participant raised an important safety concern "…Machines close to the face are dangerous". We further discuss aspects of safety within section 4.5.14.2.

5- *Punch (Overall Rank Score:36)*: Three participants thought it was among their top 3 experiences. However, four participants criticized the impact force; mentioning it should be stronger to resemble a punch. Moreover, six participants thought the end-effector was too small to convey a fist, indicating a mismatch in the visuo-haptic stimuli. We further discuss such challenge in section 4.5.14.1 .

6- Cat Rub (*Overall Rank Score:*33) had mixed views, four participants ranked this experience in their top 3. One participant said, "*Cat rubbing is my favorite, I felt the cat on my skin when it jumped at me*" and "*the cat was unexpected, it was scary but awesome*". Although mentioned comments indicate that the visuo-haptic stimuli were well synchronized, three participants complained about some discrepancy in stimuli: "*The brush is rough so I didn't like how it feels*", another added *"..it should have been softer a bit, like a cushion*". Such discrepancy made them dislike this experience.

7- *Patting (Overall Rank Score:25)* was least favored by the participants, and only two participants ranked it within their top 3. They mentioned: *"…it is the most basic action compared to all others"*, *"it is not memorable".* These comments indicate that the experience was not enjoyable. Moreover, since we used the finger end-effector to apply the pats, participants mentioned the difference in sensed feedback in comparison to the character's hands. *"The physical feel of the hand is very different"* and *"a pat should be all over my shoulder".* We conclude that the experience was not intriguing to users, and we discuss its limitations within the 4.9 Research Challenges and Future Work section.

4.5.11.2   Wearability, Comfort and Weight

On a 5-point Likert scale (5 is best), the HH was rated with 3.6 (SD=1.07) for comfort and 3.1 (SD=0.99) for weight. Several participants reported pain and pressure against the back and abdomen while wearing the HH. Aggregating the results from the previous evaluation, we conclude that the ergonomic design and weight of the HH should further be improved, especially for prolonged usage sessions.

4.5.12   Discussion and Challenges

Experiences Evaluation: The results indicate that participants generally enjoyed the experiences and had individual preferences. They rated their overall satisfaction of the HH's experiences with 4.5 (SD=0.71). Since pair-wise comparisons did not reveal significant differences between experience preferences, we conclude that each user had individual favorite experiences. Therefore, prior knowledge of the user's favorite stimuli could be used for designing customized experiences per user to increase their enjoyment.

In addition to challenges similar to those of the HS, our analysis indicates number of

particular challenges:

Visuo-Haptic mismatch: While participants did not raise notable comments about auditory feedbacks, visuo-haptic mismatch was raised by several participants, especially in the *punch* and the *patting* experiences. Participants thought that the end-effector should have resembled sensations delivered by human hands, especially in terms of surface area when patting or punching. Other participants thought the *arrow* feedback should have been sharper and stroked harder to better match the arrow in VR. We discuss a possible solution to this shortcoming in section 4.5.14.1.

Immersion and Distractions: Some participants though that robot weight, movements and the inertia of its movements broke the immersion. They especially indicated that it affected them when such movements occurred without visual stimuli (e.g. when robot moves to prepare for feedback delivery). Reducing robot's movement speed and weight could contribute to addressing these issues.

Validating Novel Feedback in VR: the HapticSnakes is capable of numerous novel haptic feedbacks, such as tugging, tapping and pinching as explained in the design space. To the best of our knowledge, the effect of these novel feedbacks on immersion and presence has not been previously investigated. Therefore, an essential future research direction is to investigate the effects of novel feedbacks on immersion and presence through comparative studies (Hoppe, Knierim et al. 2018, Ranasinghe, Eason Wai Tung et al. 2018).

4.5.13 Design Considerations of Multi-Feedback Serpentine-Shaped Robotic Wearables

Based on our HapticSnakes design and evaluation results, we identified several considerations for both designing robotic wearables with diverse feedback capabilities, and for designing user experiences based on the HapticSnakes:

4.5.13.1 Delivering Taps on Front Torso and Back

Tapping Feedback Model: Our evaluation results indicated that users had superior accuracy in determining feedback strengths over locations. Therefore, we propose the feedback model shown in Figure 47. The model provides more feedback cells on the upper regions, where users reported the highest accuracies in distinguishing tap locations. Similarly, lower cells were combined, as users were hardly able to accurately pinpoint feedback locations on these regions. On the back torso, users were found to have high accuracy in peripheral regions for distinguishing the locations of strong taps. Therefore, the back-torso model includes several peripheral and inner regions to enable delivering feedback to these regions.
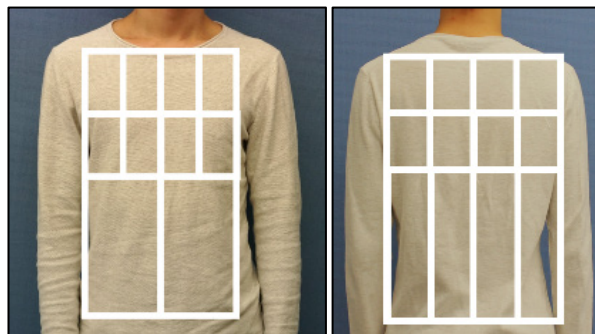
Figure 47 Based on the evaluation results, the revised feedback models have more feedback regions in the upper than in the lower regions. For the back torso, lower regions are segregated to reflect users' ability to distinguish inner and peripheral cells within lower regions.

Emphasize Feedback Strengths: As the accuracy in distinguishing tap strengths were

found to be superior to distinguishing tap locations, future robot should focus on the capability to deliver feedback with a large spectrum of intensities. Our current robot may achieve larger spectrum of feedback intensities by altering the servomotor speeds, distance of impact and torque values. Therefore, we intend to expand our work to explore the effect of applying taps with higher and lower strengths.

4.5.13.2 Designing Multi Feedback Wearables

Limb-Specific Wearables: An essential challenge of our robots is in delivering feedback to limbs within interactive VR experiences. The user's physical movements impose several difficulties on feedback delivery, such as overshooting locations or failing to deliver feedback as users move their limbs away. Therefore, smaller wearable robots can be designed to deliver feedback to moving limbs. These robots can be worn on hands and legs where they can independently deliver feedback to those regions. Wearing multiple devices could also contribute to resolving the feedback singularity shortcoming of our current designs yet could be cumbersome for users as they have to wear multiple robots.

Shape-Changing End-effectors: The rotary end-effector has several challenges. It only has 4 types of sub end-effectors and its cross-design makes it prone to accidental or unintentional feedback due to the length of each end. Shape-changing is the capability of altering various physical attributes, such as shape or texture (Rasmussen, Pedersen et al. 2012). A shape-changing end-effector, as in Figure 48, can take different shapes to convey feedback with varied attributes, like surface areas or sharpness. Moreover, feedback types can be diversified by embedding different modules, like including heat modules (Peiris, Peng et al. 2017, Ranasinghe, Jain et al. 2017, Ranasinghe, Eason Wai Tung et al. 2018) or water sprinklers, which allow for different range of feedbacks. Therefore, future research should investigate novel shape-changing end-effector designs that embed different feedback modules.
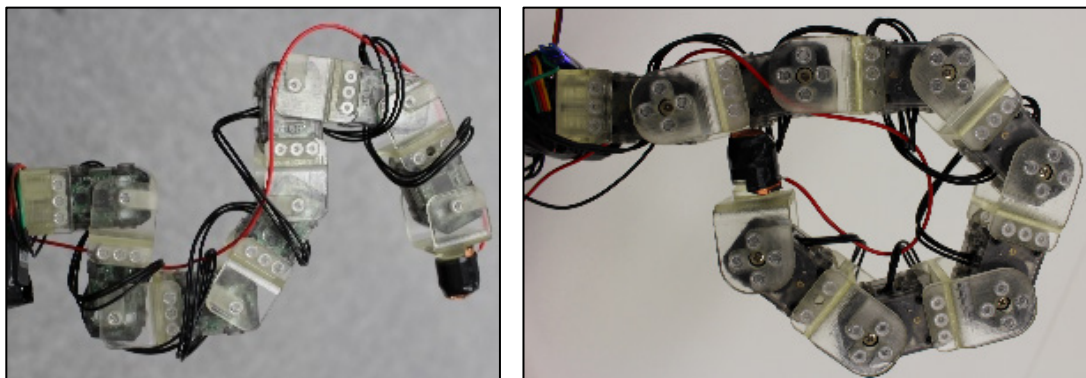
Figure 48 A tentacle shaped end-effectors with 7 DoFs. It can take different shapes, therefore providing different haptic feedbacks like shear forces with a small or large contact areas or multiple contact points.

4.5.14 Research Challenges and Future Work

In this section, we identify and discuss a number of research opportunities and challenges that arise from the design and evaluations of the HapticSnakes.

4.5.14.1 Feedback Design and Delivery Challenges

Interactive VR: Delivering feedback to the user requires prior knowledge of the user's current posture. Within interactive VR, users may constantly move and take different postures, such as when walking around a tracked space or holding and manipulating objects. Therefore, such scenarios are prone to accidental feedback (e.g. user's body bumps

unintentionally to the robot while moving), and feedback delivery failures (e.g. the user leans backwards as the robot attempts to deliver feedback on front torso, causing the robot to fail in tapping the user). The accuracy of the delivered feedback is bound by the system's ability to quickly detect and adapt the user's body movements. Therefore, we intend to integrate external tracking systems or high-speed cameras (Okumura, Oku et al. 2011, Optitrack 2019) which are widely used for VR and robotics applications. These tracking systems would enable rapid adaption of the robot's movements to users' posture or limb movements, and therefore allowing us to address mentioned challenges.

Calibration: There are several dynamic factors that should be considered to improve and automate calibration. Firstly, user's body dimensions, worn clothes, robot placements with respect to the user's body, and individual feedback preferences. Secondly, misalignments of the robot that may occur because of loosening straps or prolonged robot use. Thirdly, attributes like intensity and strength are user subjective, and they should be calibrated prior to each VR experiences to avoid visuo-haptic mismatch. Our current calibration approach is time consuming and prone to all above issues. Future work should bring advances in context awareness and machine learning to automate calibration and to cope with these changeable factors.

Singularity of Feedback: HapticSnakes is only capable of delivering feedback to one location at a time. Future work should explore other morphologies that are optimized for one or multiple types of feedbacks or body regions. Therefore, we intend to investigate extending our robot with multiple appendages and end-effectors, so that it can concurrently deliver feedback in multiple body locations.

Feedback Authoring Tools: Although our current robot control method allows recording and playing back motions with different attributes, it is cumbersome for rapid creation of different VR experiences. Therefore, matching HapticSnakes with a suitable feedback design tool is essential for exploiting its capabilities for future applications (Schneider, Israr et al. 2015). We believe a feedback authoring tool, with a graphical user interface, should fulfil two objectives. First, it should provide parametric user control over the feedback types and their attributes. For example, designers may create a tap with specific angular velocity and strength level. Second, the tool should allow designers to pair HapticSnakes's feedback with various VR events, like linking a sword-slash in VR to a swipe on the chest by the robot. Presenting these two capabilities in a user-friendly interface is critical for designing experiences based on the HapticSnakes, especially for designers and developers that do not have a background in robotics. Therefore, we intend to extend our robot control software to contain more attributes as well as a feedback designer interface to enable rapid development of intriguing user experiences.

4.5.14.2 Mechanical Design and Safety

Mechanical Structure: HapticSnakes form factor is far more capable of intriguing haptic feedback. Recent advances in tendon-based and pneumatically actuated robots are promising for this application domain, as they are generally light in weight, retain a soft structure and back-drivable (Nakata, Noda et al. , Li, Kawashima et al. 2011, Li, Kawashima et al. 2013). Such properties make them ideal for designing wearable robots that are durable, comfortable to wear and safe for daily use.

Safety: HapticSnakes biggest challenge is safety. Our robot's rapid movements to situate or deliver needed feedback and the use of high torque servomotors within close proximity to the user's body pose numerous hazards. Therefore, we intend to investigate two main directions to improve the safety of our robots. First, as previously mentioned, soft

robotic designs based on pneumatic or tendon-driven structures offer various safety features. Second, equipping the robot with sensors, such as proximity sensors or tactile sensors (Schmitz, Maiolino et al. 2011), can contribute to increasing the robots safety during operation. Therefore, we intend to investigate these sensors for use in HapticSnakes.

4.5.14.3 Further Experiences

HapticSnakes provides numerous opportunities based on novel feedback. First, HapticSnakes's feedback can be utilized for a variety of purposes. For example, to indicate different game status, like low health or to handicap limb movements during gameplay. Additional application domains are also in delivering information-rich notifications (Luzhnica, Veas et al. 2016, Al-Sada, Hoglund et al. 2019) or to break immersion in case of emergency. Future work should investigate further application domains for these emerging feedback types.

Seated VR experiences are also an interesting context for the HapticSnakes, since the challenges associated with user movements can be overcome when users are seated. Calibration and feedback delivery could be robust, as the user's body can accurately be tracked within a small workspace, such as by using depth cameras, yielding superior feedback accuracy and safety.

Beyond digital interactions, novel feedback can be utilized for augmenting users' perception, which was is an important application domain for of daily worn appendages (section 3.1.4.2). When interacting with objects, novel feedback can be used to indicate a specific the status of the robotic appendage, such as to indicate holding, manipulating or bumping into objects. Such feedback is valuable as it provides a modality beyond visual stimuli, which can be essential to reduce the mental effort during control. Moreover, novel feedback enabled by the HapticSnakes systems allows for numerous opportunities for sense-substitution and augmentation (Novich and Eagleman 2015). For example, novel feedback can be used to indicate a passing person beyond our visual field of view, or to communicate the temperature of an object through gestures. These application domains lay the ground for numerous augmentation applications that have not been previous investigated.

4.5.15 Conclusion

HapticSnakes is a waist-worn snake-like multi-robot system that can deliver a variety of novel feedback types in multiple locations. We presented two implemented robots, followed by the design space to create feedback based on our prototypes. We proceeded with an evaluation of distinguishing tap accuracies and strengths on the front torso and back. Our second evaluation investigated users' impressions of novel feedback within VR. Based on our evaluations, we extracted a number of design considerations and discussed challenges and future work.

Compared to existing works, HapticSnakes is superior in delivering multiple types of feedback in varied locations, which can have intriguing applications across different domains. However, there exists a number of trade-offs when comparing the HapticSnakes to vibrotactile wearables. For example, although HapticSnakes can deliver multiple types of feedback, there exists a number of design challenges that must be overcome to enable its effective use within mobile VR. In contrary, wearablesthat delvier feedback based on vibrotactile motors are relatively small in size and ergonomic, making them easier to embed within wearable systems. Therefore, deploying wearables based on the HapticSnakes should carefully consider the context requirements during implementation.

Realizing HapticSnakes for daily use has various challenges and requires significant

development to ensure stability and safety. We believe that future robots based on the HapticSnakes can have a huge potential in enabling realistic VR experiences and a wide array of feedback modalities for notifications and information-transfer. Therefore, the implications of the design process and evaluations are discussed within the larger domain serpentine-shaped robotic appendages, where the extracted insights are incorporated within the analysis presented in Chapter 5 and ultimately within the design considerations in Chapter 6.

Chapter 5   Design Insights

In this chapter, the research questions are addressed by extracting insights from the design, implementation and evaluations of the case studies. Each user study was first analyzed in light each concerned research question. Next, results of the design, implementation or evaluations are combined and analyzed. The insights are finally grouped under three main subsections, where each is concerned with addressing each of the research questions. Section 5.1 extracts and presents insights that focus on addressing RQ1 through an analysis and discussion of user-elicited use case distribution. Section 5.2 present various insights about social and user acceptance surrounding serpentine-shaped robotic appendages, thereby addressing RQ2. Section 5.3 addresses RQ3 by presenting design methods for creating multipurpose user experiences through different interaction paradigms, and by providing a classification of novel cross-device experiences involving serpentine-robotic appendages and various digital devices.

5.1   Daily Usage Expectations

This section addresses RQ1 *"What are the user interaction expectations and tasks associated with daily worn serpentine-shaped robotic appendages?"* To understand the daily interaction expectations, we combined and analyzed elicited results from the focus groups (preliminary studies and the case study of Orochi), enabling us to form an overall understanding of the usage expectations of serpentine-shaped wearable robotic appendages. These use cases are accordingly analyzed and discussed. Finally, the use cases are categorized, based on the type of carried actions by the robots, under three main categories, *physical interactions, digital interactions, and others*. The significance of these categories are further discussed with respect to addressing users' daily interaction expectations of serpentine-shaped robotic appendages. The analysis provides an overview of user-elicited interaction expectations, therefore enabling researchers, designers and practitioners to accommodate these interaction scenarios within future daily-used robotic appendages.

5.1.1   Analysis of Combined Use Case Distributions

In order understand the daily usage expectations of serpentine-shaped robotic appendages, the use case lists of the preliminary studies and the case study of Orochi were

first reanalyzed (Appendix 1 and Appendix 2), where duplicate and erroneous entries were removed. Next, the use cases were classified based on the updated classification (presented in Orochi's analysis), which focused on 5 primary use cases of daily worn appendages. Lastly, the use cases gathered from preliminary studies and Orochi were combined to form a use case distribution that is utilized to understand the daily usage expectations of serpentine-shaped robotic appendages. The resulting combined use case analysis comprises **457** use cases of daily use, and is shown in Figure 49. These use cases are distributed among five main categories of use, which are as follows:

- *Basic physical manipulations* (**125** use cases) include tasks such as pushing, pulling, carrying, and holding objects. Participants gave several examples of this category of interactions, where robots can be useful for basic interactions like holding objects for prolonged periods of times or reach objects that are far away.

- *Complex and Work-related Tasks* (**132** use cases) included interactions that required higher level of autonomy, intelligence or physical manipulations of professional tools. For example, assisting with house chores, using drills or screwdrivers, assist in assembly tasks, as well as using the robot to operate factory machinery.

- *Care and safety* (**102** use cases) included a variety of tasks that are concerned with preserving the safety of the user in various daily situations and providing the means to achieve comfort. Participants proposed numerous types of ways and methods the robot can maintain the safety of the user or ensure their comfort. The first subcategory resembles the direction of common health wearables (e.g. (Caon, Carrino et al. 2015, Clawson, Pater et al. 2015), which provide health monitoring and suggestions to improve users health. Users proposed use cases where the robot reminds the user to take their medications, reminds them to stand-up when they sit for too long, or to fix their posture. Compared to common wearables, the significant advantage of proposed cases is the wearable robot's ability to physically take initiative to remind users (e.g. haptic feedback) or to physically bring or give user's medication (e.g. handling objects like HapticSnakes). The second category of use cases include proactive use cases, where the robot takes initiative to protect the user through physical actions. For example, to hold the railway to prevent user's from falling when a train moves, or to physically fight-off criminals or defend users from physical harm. Overall, participants thought the robot could be smart enough to realize dangerous situations around users, and thereby prevent potential harm.

- *Interaction with Digital Devices* (**54** use cases) included tasks such as swiping a touchscreen or typing on a keyboard. Most cases emphasized interactions with a smartphone while walking, where Orochi is used to take selfies or answer the phone automatically.

- *Other tasks* (**44** use cases) included diverse use case types. First, participants proposed a number of use cases where robots can help disabled or injured users, such as acting as a prosthesis, where it can replace the user's injured or disabled limb. Another set of tasks focused on amplifying user's perceptual capabilities. For example, the robots can be equipped with microphone arrays, allowing users to listen to other persons from a far or to listen to multiple people. Similarly, they proposed that the robot can incorporate artificial intelligence to help users to infer other people's emotions through various embedded sensors (e.g. cameras for facial expressions, audio processing...etc). Some participants also proposed using the robot as a companion conversational robot (Holz, Dragone et al. 2009, Kashiwabara, Osawa et al. 2012), where the robot can entertain them through chatting. Although most of the use cases in this category do not reflect physical interactions, they indicate that multipurpose use is an essential and intriguing design factor for enabling this form of robots to be worn on daily basis.
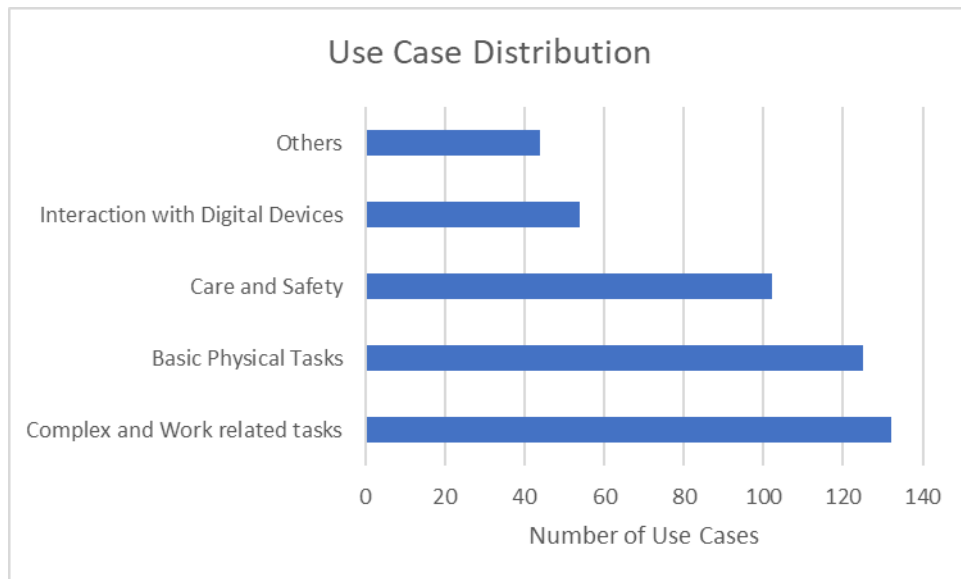
Figure 49 this chart presents the combined use case distribution based on elicited use cases from preliminary studies and Orochi's case study.

Overall, the use case distribution is a valuable resource that addresses RQ1. The distribution provides an overview of the user expectation on how such robots could play a role in our daily lives. Future works can use this comprehensive list and utilize it as basis to generate new robots and case studies based on the elicited use case list and distribution (As discussed in the Design Implications).

5.1.2 Discussion

As shown Figure 49, the primary use cases of a daily worn robotic appendages comprise *physical interaction scenarios*, classified under *basic physical manipulations*, *complex and work related tasks* and *care and safety*. These tasks constitute 78.56% of the use case distribution, therefore, they form the primary use cases of a multipurpose wearable appendage. Future researchers a designer should attempt to fulfill this category of interactions first, then attempt to achieve further interaction domains. The specifics of basic physical manipulations and complex and work related tasks is thoroughly discussed in sections 3.1.3.2 and 4.2.7.1.

Digital interactions constituted 11.82% of the total use cases. Although participants expected to use the robots mainly as a mean to operate other digital devices, previous research on haptic interfaces, shape-changing interfaces and cross-device interactions provide strong evidence that they could play an important role in day to day interactions. As evident form the preliminary studies and Orochi's case study, it is difficult to extract insights about such interactions since regular users cannot easily envision how such interactions can take place. This shortcoming is compensated with a thorough analysis of potential digital interactions that should be investigated (discussed in section 5.3.3 Digital Interaction Design) in order to increase the value of serpentine-shaped robotic appendages for daily use.

Other tasks constitute 9.63% of the overall distribution, and constituted a diverse set of use cases ranging from human-to- human communication to sense substitution. Although it is arguable that various scenarios can be accomplished through other wearables (e.g. HMDs), the main design insight of these results is that these robots are expected to be highly multipurpose. Therefore, they should include various minor functionalities in addition to essential ones makes a wearable more useful. This finding is in line with previous findings regarding general undesirability of users in wearing many systems (Clawson, Pater et al. 2015,

Lazar, Koehler et al. 2015).

By examining the flow of the focus groups, participants thoroughly discussed tasks involving physical manipulation first, then, participants proposed additional use cases which could accompany the prior raised tasks (e.g. digital tasks, sense substitution, enhancing user's perceptions…etc). Therefore, we argue that participants expect these wearable robots to be highly multipurpose, fulfilling primary use cases as a physical interaction medium followed by the other use case categories. However, we strongly believe that the existence of various use cases, with the presence of central physical manipulation scenarios, create value for these robots during daily use.

Finally, the use case distribution indicates three major categories of interactions.

1) Physical Interactions: which constitutes scenarios involving physical manipulations of objects, and thereby include the following subcategories: *Basic Physical Manipulations*, *Complex and Work-Related Tasks*, *Safety and Care*. Based on the collected information, these use cases are the backbone of which future serpentine-shaped robotic appendages should be based upon.

2) Digital Interactions: Which constitutes the secondary type of interaction. Participants presented numerous digital interactions which this form of robots can accomplish, ranging from operating smart-devices to amplifying their interaction capabilities them in different contexts. Moreover, a vast number of researches in HCI and wearable computing provided insights about digital interactions in general. Accordingly, we discuss this category thoroughly within section.

3) Other Interactions: As discussed above, these use cases present highly novel usages of wearable robots that previous works have minimally investigated. However, the collected use cases are widely diverse and minimal, therefore, it is difficult to quantify them under meaningful or distinct categories without further investigations.

5.1.3 Design Implications

The use case lists, distributions and analysis present a significant contribution that further expands our understanding of the requirements and expectations of daily worn snake-shaped robotic appendages. The distributions of use cases highlighted a diverse set of interactions that we categorized under three main categories based on the type of executed interaction: 1) Physical Interactions; 2) Digital Interactions; 3) Other Interactions. The use case distributions also underlined the importance of physical interactions as a major expectation, followed by digital interactions, and lastly other interactions.

Our analysis of gathered use cases indicate two essential design implication on future systems. *The first implication is the establishment of multipurpose use as a main design requirement.* The diversity of use cases, spanning over various physical, digital and other interactions, highlight the importance of genericity that these wearables should attain. Although such genericity is well-established as an essential trait of daily worn computing systems (Starner 2001), our analysis is the first to conclude this requirement by grounding it on user elicited use-case expectations and evaluations. Therefore, designers should consider multipurpose use as a critical design requirement of future wearable appendages that target daily usage contexts.

The second implication is concerned with how the detailed use case lists and analysis can be used as a design resource for designing and evaluating future systems. For example, future designers can create wearable appendages that target a specific set of physical interactions (e.g. augmenting users' limbs to single handedly hold multiple or large objects) and digital interactions (e.g. delivering digital notifications via novel haptic feedback

methods). Accordingly, the robots would be mechanically optimized to ensure accomplishing selected usage scenarios. Similarly, the use cases can form a base to derive evaluation metrics for evaluating existing systems, such as to gauge whether or not a certain design is capable of accomplishing a preset of physical and digital interactions. Therefore, the use case distributions and analysis bridge the knowledge gap required to design and evaluate novel or existing systems against user expectations and requirements.

5.1.4 Conclusion

This section addresses RQ1, which is concerned with understanding the interaction expectations of serpentine-shaped robotic appendages. Accordingly, data about the usage expectations from relevant focus groups is combined, structured, analyzed and discussed. The use cases were categorized under three main categories: physical interactions, digital interactions, and others. Physical interactions comprise the majority of expected use cases, which are mainly concerned with physical manipulation of objects. The secondary use cases are concerned with interactions with digital devices and contents, such as to operate or to actuate a smartphone based on different contexts. Lastly, other interactions include a diverse set of use cases that do not fall under the before-mentioned categories.

Overall, the results indicate that participants generally expect serpentine-shaped robotic appendages to be highly multipurpose. The primary use case includes physical manipulations, which covers basic physical tasks, complex and work-related tasks, and care and safety. While most of the proposed basic physical manipulations demand minimal requirements to achieve, further tasks with higher complexity demands higher level of intelligence, autonomy and context awareness to execute with minimal user intervention. These implications are thereby discussed in section 6.3 Interaction Design. Digital interactions present the secondary usage expectations for daily use. Due to the importance of this category, it is thoroughly discussed within section.

Although there exist some proposed use cases that overlap with those of wearables or devices (HMDs, smartwatches...etc), we believe that multipurpose use is the key to successful adoption of serpentine-shaped shaped robotic appendages. Therefore, although physical manipulation is an essential primary use case of this form of wearables, the inclusion of secondary use cases is essential for daily use. Although a wearable might not be as efficient in carrying out such tasks as in other purpose-made devices, yet the convenience brought by multipurpose usage could be greatly valued over efficiency, especially within daily mobile interaction contexts where highly efficient devices could be inaccessible (Clawson, Pater et al. 2015, Lazar, Koehler et al. 2015, Dementyev, Kao et al. 2016, Leigh, Denton et al. 2018). As a result, researchers and practitioners should embody both primary and secondary use cases within future robot designs that target daily use.

Overall, the significance of presented insights lies in the fact that it is the first effort that specifically addresses the daily usage expectations of serpentine-shaped robotic appendages. Such knowledge is significant in both expending our understanding of this form of wearable robots, as well as enabling designers and practitioners to establish design and evaluation metrics on which wearables that target daily use can be gauged against. Therefore, we believe that such knowledge should enable designers and researchers to create new case studies based on the presented insights, thereby advancing this research domain further.

5.2   Social and User Acceptance

In order to address RQ2 *"What are the main social and user acceptability challenges? And how can we address these challenges?".* two main directions are pursued to extract needed insights. First to address social acceptability, and second, to address user acceptability, where both challenges are synonymous with wearable systems. Social acceptability reflect methods of addressing how a wearable is perceived when worn an used in public (Rekimoto 2001, Dobbelstein, Hock et al. 2015), while user acceptability is concerned with factors effecting adoption and personal usability of a wearable system (Koelle, Ali et al. 2017). We emphasized the analysis on the first and second case studies (Orochi and HapticSnakes), which tackled relevant aspects of social and user acceptability while using serpentine-shaped robotic appendages.

First, to address social acceptability (section 5.2.1), we extract insights regarding unobtrusiveness from the evaluation results of Orochi, which highlighted the need for robotic shapes and aesthetics that drew a minimal amount of attention. Further insights are also extracted from Orochi's evaluation, where aspects of social acceptance are discussed. Various interleaved factors effect social acceptance, ranging from the way the wearable is used to whether or not others use similar wearables. We argue that while some of the factors affecting social acceptability are identified, deeper studies are required to completely understand these challenges.

Second, in order to address user acceptance, the evaluation results of Orochi and HapticSerpent's are analyzed, and conclude two main factors can affect user adoption of these wearable robots (section 5.2.2). First, undesired interactions, which present a number of interactions that would repel users from using such robots. HapticSerpent provide insights about various body locations which users though are unacceptable to receive haptic feedback at. Secondly, undesired use cases, which presents contexts on which using this form of robots is deemed socially or culturally inappropriate. Insights from Orochi's evaluations provides significant insights about use cases where the usability of the robot was totally undesired.

Accordingly, we discuss the implications of such insights on designing future systems, and provide a conclusion.

5.2.1   Addressing Social Acceptance

Previous works on social acceptance constitutes numerous interleaved factors that affect acceptance of a certain wearable device, ranging from novel aesthetics to novel interaction (Dobbelstein, Hock et al. 2015, Profita 2016, Schwind, Deierlein et al. 2019). Therefore, the use cases tackled two essential domain of challenges to address daily usage:

1- *Unobtrusiveness in Public:* This aspect is addressed through Orochi's design and evaluation. The limber body of the robot and its fabric cover enabled Orochi to be largely perceived as a garment. Such aspect is further confirmed through the survey results, which generally indicate that Orochi drew minimal amount of undesired attention when worn in public and especially when worn to resemble a typical garment. Therefore, such results indicate that our approach in addressing this challenge is successful, and thereby can be applied in similar wearable robotic appendages.

2- *Social acceptability of interactions:* Previous works have highlighted that wearables with novel aesthetics or those enabling novel interactions can subject users to different aspects of sociocultural pressure, such as judgement and social isolation (Profita 2016, Schwind, Deierlein et al. 2019) . Similarly, Orochi's evaluations point out similar essential challenges in social acceptability when in use. First, insights from Orochi's evaluations indicated that a major reason of Orochi's noticeability is *"the way it is used"*, which therefore indicate

that the novelty of interaction is a major reason for drawing undesired attention. This is further supported by the survey results which also showed that Orochi draws more attention when in use. However, survey results also indicated that participants are willing wear Orochi in public despite its flaws (m=4.425, SD= 1.52). These results indicate that the opinions and popularity of novel wearable robots within the society is one factor in determining individual adoption of such wearables.

Despite the maturity of the hardware, novel wearables, like Google Glass, has faced similar difficulties with social acceptability, where wearers where discriminated, ashamed or banned from entrance to certain locations (CNBC 2019, Telegraph 2019). These difficulties indicate the interleaved challenges of social acceptability. To the best of our knowledge, there is a dearth of studies that tackled social acceptability of wearable robotic systems. Therefore, similar to ongoing efforts in studying acceptability factors of smart glasses (Hsieh, Jylh et al. 2016, Koelle, Ali et al. 2017), this direction of studies should be conducted with emphasis on serpentine-shaped robotic appendages (Further discussion in section 7.2).

5.2.2 Addressing User Acceptability

From users' standpoint, the functional ability of a wearable robot to perform its intended tasks is essential. However, acceptance, adoption and daily use of a wearable system comprise additional equally essential non-functional requirements during daily use (Lazar, Koehler et al. 2015). The evaluation results of Orochi and HapticSerpent provide a number of insights regarding user acceptance about of serpentine-shaped wearable appendages. These insights are classified under two main categories:

1- *Undesired and Controversial Use Cases:* From Orochi's evaluations (Summarized in Table 2), participants highlighted use cases where it was undesirable to use a robot. First, interactions requiring very precise movements, such as to apply ointment to the user's eyes. Participant's emphasized that it is difficult to trust the robot with critical tasks that may injure the human, and thought they would trust humans to carry out such tasks. Second, using the robot in critical or unstable situations, such as while exercising or during an emergency. Participants argued that the robot would not be smart enough to completely realize the criticality of critical situations, and therefore could pose potential danger during such scenarios. Thus, many participants suggested shutting-off the robot during such situations. Third, handling humans or animals, such as holding babies or petting companion pets. They raised several trust and acceptability issues, as they though the robot is not trust-worthy of such actions due to potential failure or harm to people or animals. Similarly, social acceptability of such actions was a major concern. For example, it may not be acceptable to shake people's hands using the robot, as participants though it could be rude to do so.

2- *Undesired Interactions:* The novelty of snake-shaped robotic appendages raise unexplored acceptability challenges, especially with unprecedented novel interactions. A solid example of such interactions is the acceptability of receiving novel haptic feedback in different body regions, which was studied as part of the HapticSerpent project. The results of the conducted evaluations enabled us to extract initial insights about the acceptability of receiving novel haptic feedback in various body locations; the feedback heat-map (in Figure 27) provides overall guidance to locations where haptic feedback is acceptable to be received around the body. Although users were strongly opinionated in various feedback regions, they expressed mixed views in sensitive (head or hips) or uncommon regions (e.g. upper or lower feet). Such results indicate that there could be further contributing factors, such as intrinsic motivations or preferences, that may affect the user's opinions within such regions. Overall, the heat-map forms a basis from which future work should build upon by investigating haptic feedback within most desired body

locations, while avoiding undesirable ones.

Very precise tasks (applying eye ointment)	Hugging partner or family member	Holding a child's hands
Usage during disasters (potential unreliability or failure of the robot)	Food preparation (e.g. user wants to touch and feel the ingredients	Holding a baby or a child
Cooking (user wants to feel viscosity or tenderness of food while cooking)	While exercising (the robot can get caught in user clothes or impede user movement)	Shaking other people's hands
Holding or petting animals	While snowboarding, running or bike riding. (The robot can cause more harm if user falls on the robot or vice-versa)	During Disasters (the robot can impede user's movement while escaping)

Table 2 summarizes the main categories of tasks and contexts where using Orochi was undesirable.

5.2.3 Design Implications

Social acceptability plays an essential role in enabling daily use of wearable systems (Rekimoto 2001, Dobbelstein, Hock et al. 2015, Profita 2016, Alallah, Neshati et al. 2018). Such importance extends to daily worn appendages, where we have shown how to address social acceptability challenges within the scope of wearable robotic appendages. In this dissertation, we focused on two dimensions of social acceptability, when the robots are retracted and when in use. When worn and retracted, *designers should address social acceptability by designing wearable robotic appendages with unobtrusive designs.* One direction to realize unobtrusive designs is demonstrated in Orochi, where it resembled common garments, such as a scarf or a belt, both in terms of shape and aesthetics. Similarly, future systems can achieve unobtrusiveness by embracing similar design directions with other types of garments or wearable accessories (e.g. purses or backpacks). These accessories are in turn widely acceptable and draw minimal amount of attention when worn publicly.

Similar to novel wearables and interaction methods (Rekimoto 2001, Dobbelstein, Hock et al. 2015), our results show that wearable robotic appendage can draw relatively high levels of undesired attention when in use (section 4.2.8.1). Such undesired attention can in turn yield high social pressure that eventually results in abandoning the wearable device (Profita 2016). However, unlike research in wearable computing or assistive systems, the challenges of interaction in public are largely not understood in wearable robots, and especially in wearable robotic appendages.

Accordingly, *an important design implication is the execution of social acceptability evaluations targeting specific interactions and contexts as an integral step in the design process of such systems.* For example, a user study can be conducted to understand the social acceptability of carrying-out physical manipulation tasks in public, by using surveys, focus groups or in the wild-studies (Messeter and Molenaar 2012, Koelle, Kranz et al. 2015, Alallah, Neshati et al. 2018). For example, in Orochi's evaluation, we investigated obtrusiveness of Orochi when worn and used in public, where we have found out that Orochi draws much more undesired attention when in use (as shown in Figure 50). Accordingly, the results of social acceptability evaluations should form the basis from which interaction design of this form of wearable robots can be constructed; especially, identifying which interactions raise highest challenges and providing the methods to address these challenges. In conclusion, this form of

evaluations is essential and should be conducted as part of the design process of wearable robotic appendages.

Average Score	2.95	3.88	4.43
SD	1.43	1.38	1.30

Figure 50 this figure shows the interrelation between public usability of Orochi and associated undesired attention it draws. When Orochi is almost worn like a scarf and close to the body (Left), Orochi was not very noticeable (its score is relatively low). However, when Orochi is worn and used in an abnormal way, such as when worn in a way not resembling common garments or when used for a highly novel task, it can draw a lot of attention (middle and right).

User acceptance constitute two main factors that affect adoption and usage of serpentine-shaped robotic appendages, and our evaluation and analysis results highlight two main domains. First, potential users raised undesired and controversial use cases surrounding this form of wearable robots. These use cases are limited to physical manipulations, but also span to digital interactions, as the evaluation results also indicated that acceptability of haptic feedback is dependent on delivered body location (in Figure 27). Therefore, we believe the insights gathered from controversial and undesired use cases and interactions complement the prior user's interaction expectations presented in the use case distributions (section 5.1.3), as they highlight the boundaries of the purpose domains of this form of wearables. Although it is essential to design wearables that meet specific usage expectations, avoiding unwanted use cases, that may frustrate, confuse or can cause potential harm are equally important in realizing interactive systems (Heyer and Husoy 2012, Taylor, Dey et al. 2015, Vasiete and Yeh 2015, Garg and Kim 2018, Goetsu and Sakai 2019, O'Kane, Aliomar et al. 2019). *Therefore, an important design implication is the establishment and understanding of the boundary surrounding multipurpose use, so that undesired and controversial interactions are avoided.*

5.2.4 Conclusion

Overall, social and user acceptance comprise a number of interleaved factors. In this dissertation, we extract a number of insights regarding such challenge, where these insights analyzed, categorized and presented in this section. Previous works suggested that numerous interleaved factors affect the social acceptance of technology in general. Previous literatures about wearable systems provide various evidence that social and user acceptance are essential factors of daily use (Dobbelstein, Hock et al. 2015, Lazar, Koehler et al. 2015, O'Kane, Aliomar et al. 2019, Schwind, Deierlein et al. 2019), and so they should be identified and addressed in order to realize serpentine-shaped robotic appendages.

As related works about social acceptance challenges of wearable robots are generally scarce, this dissertation contributes with significant insights to address this challenge. First, we address unobtrusiveness during public use by proposing robotic designs that resemble

common garments and accessories, and the evaluation results indicate the effectiveness of this approach (i.e. Orochi, section 4.2.8). Second, social acceptance of using such wearables in our modern society depends interleaved challenges. Our analysis suggests that one important dimension of acceptability is how common these wearables are, as the popularity of these wearable robots within the community could encourage people to adopt and use these wearables on daily basis.

The usability of a daily worn robot is subject to various personal acceptability challenges. This dissertation also bridges this gap by providing a fundamental analysis of the challenges surrounding daily use, grounded on extracted insights from the design, implementation and evaluations of the case studies. We classify these factors in two categories. First, some factors are related to the acceptability of the use cases, where some use case should be avoided when designing such wearable robots. Second, other factors require much more careful attention, as even if fundamental interactions could be generally acceptable based on existing literatures (e.g. haptic feedback), applying such interactions in specific contexts, such as on a specific body region, delicate or critical tasks, could raise unforeseen acceptability challenges. These insights form the baseline from which future works should expand our insights by conducting deeper investigations and addressing these challenges prior to deploying future wearable systems.

5.3   User Experience Design

This section addresses RQ3 *"How can we design cohesive and cross-contextual user experiences for this form of wearable devices? "*. To address this research question, two main challenges should be tackled. First, *how can we design a user experience that copes with and supports multipurpose use?* The second challenge is *how can we incorporate novel interaction experiences, enabled by serpentine-shaped robotic appendages?* Accordingly, three case studies are analyzed in order to extract required insights, which are Orochi, weARable and HapticSnakes. Orochi's evaluations provided initial evidence that address the interaction expectations, underlining the need for two main interaction paradigms. WeARable follows by investigating how these interaction paradigms can be embodied within one coherent multipurpose experience. The novel experiences developed in Orochi and HapticSnakes provide various insights toward developing digital interactions that seamlessly combine serpentine-shaped robotic appendages and digital devices and services. Therefore, the designed experiences are used as a basis for extracting insights about designing digital interactions.

The before mentioned challenges are addressed as follows: The first challenge is addressed through eliciting and analyzing insights gathered from the evaluations of Orochi, as well as the design, and implementation of wearable (discussed in sections 5.3.1 and 5.3.2). The second challenge is addressed by eliciting, structuring and incorporating novel interactions within found in the first, third and fourth case studies, which is addressed in section 5.3.3. Accordingly, we group and discuss relevant insights within each of the subsections as follows:

5.3.1   Designing Multipurpose Interaction Experiences

Designing cohesive multipurpose user experience is a fundamental challenge realizing multipurpose wearables. This challenge has been first highlighted in the preliminary studies by HCI experts (section 3.2.4), and later specifically addressed within the design and evaluation of the third and fourth case studies (sections 4.4 and 4.5). Specifically, this challenge is addressed in the third case study (weARable) which presents the concept of intrinsic interactions; a category of interactions concerned with controlling the inner state of

the robot. For example, to manipulate the movement speeds, current poses. Additionally, allowing users to see selectable mode of operations, including various poses for retracting the robot, or to select different purposes or applications. This sort of interaction allows users to control a multipurpose robot efficiently, enabling a sense of transparency and control over the wearable robot.

As embodied in weARable, we demonstrated a menu-based system that allows users to retract or wake-up the robot as required. In addition, select among different purposes and applications, as well as exiting different modes. Accordingly, intrinsic interactions are the basis on which all inner robotic attributes can be controlled, and all interaction experiences can be viewed, launched or exited by the user.

5.3.2 Interaction Paradigms

Insights from Orochi's evaluation indicate that users mainly had two interaction paradigms: as *a tool* and as *an agent*. Each interaction paradigm has different interaction requirements and expectations, and we discuss them as follows:

1- As augmentation tool: In this role, participants generally perceived the robot as a mean for extending users' physical interaction capabilities. For example, to extend users' ability to hold large objects in one hand, or to reach objects from afar. In this mode, the robot is reactive to and reflective of the users' explicit intent, and merely a mean to achieve the users' interaction objectives.

2- As a companion. In this mode, the robot is expected to be highly independent from the user, exhibiting high autonomy and intelligence. Participants also expected the robot to exhibit anthropomorphic traits, like conversational robots, and can take the initiative to execute tasks proactively without user initiation or with minimal intervention.

Each of these interaction paradigms (as a tool and as a companion) have different implications on the user experience design. Explicit interactions are often associated with using the robot as a mean, where the actions of the robot are specifically determined by the user. In contrary, implicit interactions are associated with interacting with the robot as a companion, where it is expected to be highly autonomous and intelligent with anthropomorphic interaction modalities (such as eye gaze or speech (Fink 2012)).

Accordingly, daily usage requires embodying both interaction paradigms within the interaction experience. Therefore, the third case study, weARable (section 4.4), demonstrates how both of these paradigms can coexist within the user experience. As a tool, weARable can be used for a variety of physical manipulations, such as holding, pushing and pulling objects. To execute various physical manipulations, the user has to explicitly initiate and select the desired physical manipulation and the object to execute the manipulation on from the AR menu. Moreover, users can select specific poses the robot can partake in order to assist in holding objects (as shown in Figure 51). Therefore, although this method provides some level of autonomy to execute the manipulations, the action and its specifications has to be initiated and selected by the user, respectively. As an agent, weARable is able to display an agent character in AR above the robot, providing the robotic appendage with various anthropomorphic expressive capabilities. The overlaid companion character can interact with the user in a variety of modalities, including haptic, shape-shifting, and auditory interactions. The character also responds to various inputs, such as touch, gaze and voice commands.

Figure 51 (Left) the AR menu allows the user to control intrinsic attributes and access/exit various modes of operation and experiences. (Middle) Users can select various poses and actions form the AR menu to support different physical manipulation needs. (Right) The companion character can provide auditory, shape-shifting and haptic interaction experiences.

The daily interaction experience of serpentine-shaped robotic appendages comprises two main paradigms, as a tool and as a companion. Each of these paradigms have different interaction requirements and implications. Evidence from the first case study (section 4.2) underlines the importance of these two different paradigms within daily use. Therefore, these paradigms were realized in the third case study (section 4.4), where we demonstrate how an interaction experience can be developed so it incorporates both of these paradigms. Overall, it is important for daily worn robots to incorporate both of these paradigms within the interaction experience, as different contexts have different user interaction expectations that should be met with either of these paradigms. Therefore, the design and implementation implications are further discussed in section 6.3 as part of the Design Considerations.

5.3.3 Digital Interaction Design

Although digital interactions are an integral part of multipurpose use, there is a dearth of studies that attempted to identify and structure cross-device interactions with wearable robots, and especially serpentine-shaped appendages. Therefore, this section provides an overview of potential cross-device interactions using serpentine-shaped robotic appendages and other devices or services. Cross-device experiences are interactions that combine the wearable robot and a digital device to carry-out a digital interaction. From our work, we present three categories of interactions that we have explored, which are as follows:

5.3.3.1 Operating Other Devices

A wearable serpentine-shaped robotic appendage may be used to operate various devices, whether reflecting the user's intention or independently. As shown in Figure 52, Orochi can be used to operate a smartphone. In this scenario, the carried-out actions can be directly triggered by the user using one of the implemented control methods. Similarly, other digital devices can be used, such as to type on a keyboard.
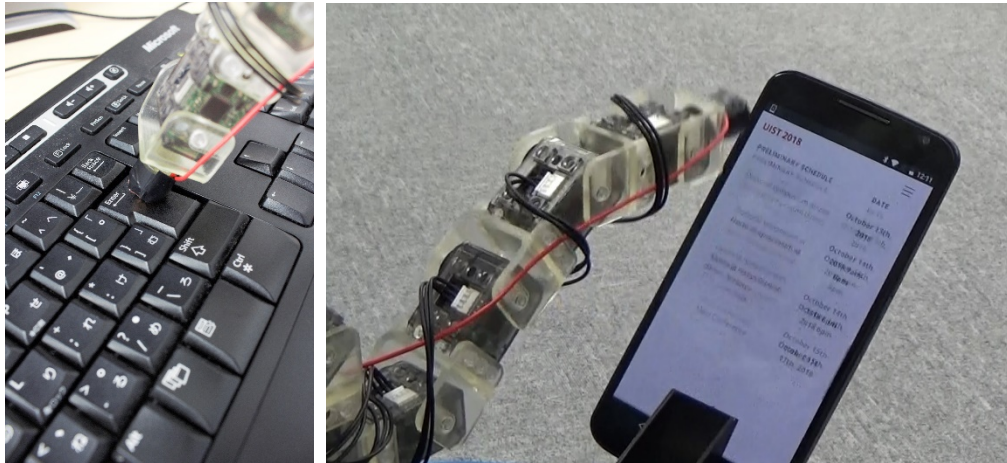
Figure 52 Orochi can be used to operate various digital devices

5.3.3.2   Augmenting Smart Devices

Serpentine-shaped robotic wearables can complement or amplify a smart-devices interaction through highly expressive input and output modalities. For example, Orochi can complement a smartphone to have extended expressible modalities. The smartphone can be actuated and moved, such as to answer phone calls automatically (Figure 53), or to indicate where the user should go in a navigation application. In this application, Orochi and the smartphone present a unified user experience, thereby enabling the smartphone to be augmented by Orochi's physical manipulation capabilities.

Figure 53 (left) when the user selects to answer the phone call, (right) the robot automatically brings the phone to his head to talk. In this scenario, Orochi augments the smartphone with actuation capabilities, which can be used to develop enhance trivial smartphone applications.

Figure 54 A navigation application is developed, which demonstrates how a serpentine-shaped wearable appendage can be used to amplify the interaction capabilities of a smartphone. In the pictures, the robot automatically leans in various directions to indicate where the user should be heading based on navigation information.

5.3.3.3   *Always Available Interface (AAI)*

This category of interactions allows the wearable robot to act as a proxy interface to various systems or devices, where it can be intermittently used as a tool for providing input or output methods. This mode of operation is demonstrated in the third case study (weARable), where we presented how the robot can both act as a haptic feedback or an input medium to interact with AR contents. Haptic interactions are also a subcategory of AAI, which we thoroughly examined in the HapticSnakes project. HapticSnakes provide a design space (Figure 41) to construct various experiences using serpentine-shaped robotic appendages. These feedback types can be used in a variety of application domains. For example, for enhancing immersion (as applied using the HapticSnakes) or for conveying information-rich notifications or haptic feedback.

5.3.4   Design Implications

The user study results of Orochi underlines the importance of partaking two main interaction roles, as a tool and as a companion. In weARable, we realize how such expectation can be realized by delivering a design space providing multiple experiences that fall under each of the interaction paradigms. Although some existing works briefly discussed the potential need for multiple interaction paradigms (Leigh and Maes 2016), such assumptions were not grounded on user elicited data. Therefore, this dissertation is the first to ground the requirement of developing daily usage experiences on multiple interaction paradigms to cope with the dynamics of daily use. *Accordingly, this finding establishes the importance of embedding both interaction paradigms within the daily user experience.*

Each interaction paradigm has a list of associated expectation-traits and interaction implications, which are summarized in Table 3. As a *tool*, users tend to desire manual control methods with high DOFs, enabling them to dexterously control the robot. As a *companion*, users desire more implicate, highly autonomous and anthropomorphic interaction methods, allowing the robot to support user's as an agent/companion. Unlike existing wearables that utilize a singular interaction paradigm (e.g. (Wu and Asada 2014, Saraiji, Sasaki et al. 2018)), *future systems should be designed to incorporate both interaction paradigms, where the selection of appropriate the paradigm depends on the design and contextual specifications* (e.g. task type, user expectations and other factors, desired amount of dexterity given to the

user in a specific task, amount of user's available cognitive or physical resources that can be allocated for the task). A design process is introduced in 6.3 to facilitate the development of experiences based on these two paradigms.

	As a tool	As a Companion
Interaction	Explicit	Implicit
Traits	Dependent, Reflective of user's input and intent	Highly Independent, High autonomy and intelligence
Implications on Control Methods	EMG-Synergetic Control, passing control to user's limb	Anthropomorphic interactions Facial expressions, gaze and speech

Table 3 this table summarized and interaction paradigms, their associated traits and implications on control methods.

Novel digital interactions comprise an essential part of daily usage expectations. However, few research literatures have tackled the problem of digital interactions with daily worn robots, and specifically cross-device user experiences (Dementyev, Kao et al. 2016, Leigh and Maes 2016, Leigh, Denton et al. 2018). Therefore, this dissertation fulfills a critical user requirement by identifying and structuring novel digital experiences combing serpentine-shaped robots and digital devices and experiences. Based on our analysis in section 5.3.3, we summarize digital experiences under three main categories shown in Table 4. Based on our results and analysis, digital experiences are an integral aspect of daily interactions. Therefore, *an important design implication is the inclusion of digital interactions as an integral and inseparable part of the user experience and alongside physical interactions* (as discussed in 5.1.3). Especially, use cases involving smartphones, as smartphones are daily used devices, and users expected smartphones and daily worn serpentine-shaped robots to be actively interactive in novel ways.
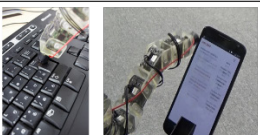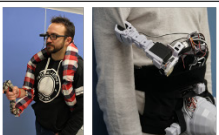
	Operating Other Devices	Augmenting Smart Devices	Always Available Interface
Trait	Robot utilizes end-effectors to physical interface with a device	Robot and Device cohesively communicate and deliver a user experience	Robot is intermittently used as an input or output medium for different device or service
Example Experiences			

Table 4 provides a classification of digital experiences based on our developed use cases

5.3.5 Conclusion

This section focuses on addressing the third research question, which is mainly concerned with designing cohesive user experiences for serpentine-shaped robotic appendages. To address this research question, we elicited insights from the first and third case studies, which addressed the need for users to control intrinsic wearable attributes as well as invoke/exit various modes of operation. Additionally, we elicit further usability insights, where we indicate that each task can be executed under two main paradigms, as a tool and as a companion. These insights are significant for expanding the overall understanding of how user experiences can be designed for multipurpose wearables in general, and especially serpentine-shaped robotic limbs. For example, researchers can prototype similar intrinsic interaction menus to enable controlling inner attributes through other modalities, such as voice commands. Likewise, future works can develop a menu to invoke and control the robot through an attached touch display. Overall, meeting these two

requirements is fundamental for designing multipurpose wearables, and this section demonstrated how to address these essential interaction challenges.

In addition, user interaction expectations of serpentine-shaped robotic appendages are realized through the third case study, where we show how interactions can be designed using two main paradigms: as a tool and as a companion. Each of these paradigms have design and implementation implications which are thoroughly discussed in section 6.3.1. Lastly, we structured digital interactions into three main categories: *operating other devices*, *augmenting smart devices*, and *AAI*. This classification provides valuable insights through a variety of examples of how to the case studies embodies each of these digital interactions within daily usage contexts. Additional significant contributions are made in the fourth case study (HapticSnakes) which provided elaborate design space and feedback delivery matrix grounded on the evaluations. Such contributions are key for designing future haptic feedback using this form of wearable robots.

Overall, the insights present significant contributions towards designing user experiences for multipurpose wearable robots. Specifically, the methodology of designing a multipurpose user experience that allows users to switch between various usage modes and interaction paradigms, is a novel contribution that have not been addressed in previous in multipurpose wearables (e.g. (Dementyev, Kao et al. 2016, Leigh and Maes 2016, Leigh, Denton et al. 2018)). Such results are essential for providing researchers with methods and directions to design a cohesive user experiences for multipurpose wearables in general, and especially serpentine-shaped robotic appendages. Moreover, the identification and categorization of novel cross-device interactions provides a structured overview of novel interactions that are enabled through combining digital devices and wearable robotic appendages. Such contribution should inspire and guide future works to emphasize the potential of such novel experiences when designing serpentine-shaped robotic appendages for the daily usage contexts.

Chapter 6 Design Considerations

This chapter addresses the fourth research question *"From the perspective of multipurpose use, social acceptance during public use, and cross-contextual user experiences, what are the main design considerations required for realizing serpentine-shaped robotic appendages?"*. Based on the preliminary studies and the design, implementation, and evaluation process of the case studies, four categories of design considerations are extracted and structured and presented in this chapter. The first design consideration is *multipurpose domain*, which is mainly concerned with the design for multipurpose use, covering the design insights and methods for fulfilling such consideration. The second design consideration is *Interaction Design*, which provides guidelines for developing user experiences based on interaction paradigms and interaction modalities. The third design consideration is *wearability* and ergonomics, where we give an overview of the possibilities of designing serpentine-shaped robotic appendages with varied wearability paradigms and attachment methods. The fourth design consideration is *Unobtrusiveness in Public Contexts*, which is concerned with designing serpentine-shaped robotic appendages with the aim of minimizing undesired attention when publicly worn and used.

Although We believe the design insights (Chapter 5) provide an overview of the main design factors required to realize this form of wearable systems, the design considerations provide a structure and an embodiment of the main factors needed to design, implement or evaluate serpentine-shaped robotic appendages. First, previous works indicated that realizing wearable systems for daily use requires fulfilling numerous interleaved factors (Sears, Lin et al. 2003, Tamminen, Oulasvirta et al. 2004, Barnard, Yi et al. 2006). Accordingly, the design considerations address such requirement by presenting four primary factors. These factors comprise both theoretical design guidelines for meeting various criterion of daily use, and implementation methodologies of fulfilling these varied requirements. As existing surveyed literatures do not fulfill all the design considerations required for daily use, our contribution provides researchers with a semi-systematic method of identifying and fulfilling the main design factors required to design and implement serpentine-shaped robotic appendages that target daily use. This aspect is important for both researchers and practitioners, assisting in the efforts to replicate the case studies, to create new and novel case studies, or to evaluate existing whether or not a case study fulfills these design considerations. Second, the design insights (Chapter 5) and the design considerations provide an indication of current research

progress in serpentine-shaped robotic appendages, which form the basis to advance future research in this domain. Researchers can conduct further work in a variety of methods, such as to broaden our understanding of a specific design consideration (e.g. social acceptability) or to develop and evaluate new means to fulfil a specific design consideration (e.g. achieve unobtrusiveness through a new form factor). Therefore, the design insights and considerations are beneficial for both researchers and practitioners, and can thereby utilized in the design or evaluation process of a serpentine-shaped robotic appendage.

In the following sections, each of the design considerations is thoroughly discussed. We start with an overview and a suggested design considerations' implementation flow (section 6.1). Next, we discuss each of the design considerations (sections Multipurpose Use6.2 to 6.5). Section 6.6 discusses implementation methodologies to embody each of the design considerations, in addition to discussions about trade-offs related to structural flexibility and sensorization of serpentine-shaped robotic appendages.

6.1 Overview of the Design Considerations

The extracted design considerations can be used in a variety of methods. For example, to enhance existing wearable robotic appendages designs, or to evaluate them for compliance with the extracted insights. However, in this section, we provide a systematic approach for utilizing the design considerations mainly for designing future wearable robotic appendages. The proposed approach can be utilized by both designers, researchers or practitioners who are interested in designing serpentine-shaped robotic appendages for everyday use. Each of the design considerations are discussed within sections 6.2 to 6.5.

In Figure 55, we present an overview of the design considerations and their associated dimensions. To utilize the design considerations, we propose a top-down flow (1-4) to sequentially determine the dimensions within each design consideration category, thereby ensuring the robot's compliance with requirements and expectations of everyday use. The flow, which starts at designating the task domain and ends with public use, was mainly based on the insights gathered from preliminary studies with robotics experts (section 3.2); who strongly recommended designating the task domain prior to designing the technical components of the robots, which is a common procedure in robot design processes (Angeles and Park 2008). Therefore, with the exception of step 1, steps 2 to 4 are interchangeable and can be executed in different orders.

1) Task Domain		Physical Tasks	Digital Tasks		Other Tasks
2) Interaction Design	Interaction Paradigm	As a Companion		As a Tool	
	Autonomy Level	Highly Autonomous	Semi Autonomous	Minimally Autonomous	
	Modality	Anthropomorphic Interactions	Hybrid	High DoF (Manual Controls)	
3) Wearability and Ergonomics	Attachment paradigm and locations	Fixed	Semi Dynamic	Dynamic	
4) Unobtrusiveness and Social Acceptability	When Disengaged	Resembling Garments	Resembling Accessories	Retractability	
	When Engaged	Social Acceptability evaluations (per designated task)			

Figure 55 an overview of the design considerations and dimensions.

We summarize the flow of embodying the design considerations in 4 main steps:

1- Designating Task Domain: The designers should first consider the task domains of the appendage to be designed. As indicated in section 5.1, we extracted and presented a number of task categories, covering physical, digital and other tasks. Based on our gathered evidence regarding the task importance, we believe designers should primarily consider multiple physical and digital interactions, followed by other interactions. We

believe that the analysis of the categories in section 5.1.3, and also the detailed scenarios presented in appendix 1 and 2 that can be used as basis to designate the task domain. This dimension is further discussed in section 6.2, and section 6.6.1 provides various methods of implementing multipurpose use in serpentine-shaped robotic appendages.

2- Interaction Design: Designers should consider how and which interactions are going to take place between the user and system to achieve each designated task. As discussed in section 5.3, interaction can take place utilizing two main paradigms, which have various implications on the interaction modalities and level of automation. Therefore, we discuss various methods of designing interactions based on two interaction paradigms (6.3), and provide implementation specifications to embody each dimension (6.6.2).

3- Wearability and Ergonomics: designers should consider the attachment paradigm and attachment location desired for the robot. This dimension constitutes three main wearability methods, each providing a different level of flexibility in wearing the robot in various locations around the body. For example, if the robot should only be worn in one specific location, designers should consider a matching attachment method (e.g. using belts or straps…etc). Another dimension to consider is the worn locations, where such location (or locations) should be determined based on the task domain, as it determines the accessible workspace surrounding the robot. For example, if a designated task is to assist users in single-handedly grasp large object, the worn location of the robot should be selected in such away it provides an accessible workspace around the user's hands. Section 6.4 further discusses the dimensions required to embody this design consideration, and section 6.6.3 provided various methods to embody this design consideration.

4- This step is mainly concerned with addressing public usage challenges. When the robot is not in use (*disengaged*), designers should consider how to attain unobtrusiveness, such as by resembling garments or accessories. Another important factor is the ability for the robot to retract and fold away when not in use. When the robot is used publicly (*engaged*), designers should consider the social implications of each desired scenario through obtrusiveness evaluations. These design dimensions are essential for embodying an unobtrusive robot design, and they are thoroughly discussed in section 6.5. Methods of embodying this design consideration are discussed in section 6.6.4

Methods of embodying the design considerations, as well as trade-offs in implementing them are discussed in section 6.6. Overall, we believe the design considerations, dimensions, and utilization flow provide both a design and implementation methodology toward systematic fulfilment of daily usage requirements. We also believe the design considerations provide a foundation toward ultimately constructing a framework or design space that can compressively integrate multidimensional factors covering a multitude of design domains (Goodwin and Winfield 2008, Haeuslschmid, Pfleging et al. 2016).

6.2   Multipurpose Use

Multipurpose use is a core design consideration. Various previous works on wearable computing have established that it is a fundamental requirement and an expectation for daily use (Starner 2001, Clawson, Pater et al. 2015, Lazar, Koehler et al. 2015, Leigh and Maes 2016). Evidence from the conducted preliminary studies have shown that participants regard multipurpose use as an essential factor, providing different methods on how such considerations can be fulfilled. Our evaluation of Orochi have also shown that participants regarded Orochi's flexibility as one of its most highly regarded traits. Based on such evidence, we conclude that multipurpose use is a critical design factor for designing and constructing

daily used serpentine-shaped robotic appendages.

From an implementation perspective, realizing which tasks a serpentine-shaped robotic appendage should accomplish is important to consider. First, designating which daily tasks a serpentine-shaped robotic appendage is designed to accomplish enabled designers to optimize the mechanical design for achieving chosen tasks. For example, if the robot is designed for physical manipulation, knowing which objects the robot is supposed to manipulate and what type of manipulations are required are important for optimizing the mechanical design to handle such objects. Second, designating the purpose domain allows designers to study and gauge the robot's effectiveness in carrying out specified daily tasks. For example, if a serpentine-shaped robotic appendage is designed to deliver novel feedback, the robot may be evaluated based on the presented design space in the HapticSnakes, which provides a detailed dimension covering possible experiences and design attributes.

Based on the insight's analysis in section 5.1, The domains are classified to primary, secondary and other interactions. To achieve multipurpose use, designers should emphasize fulfilling primary use cases first, then secondary ones. Other use cases can also be realized, but the criticality of these use cases during daily use is yet to be evaluated:

1- Physical Interactions: this category of interactions comprise basic physical manipulations, complex and work-related tasks, and use cases that ensure the safety and comfort of users.

2- Digital Interactions: This category covers interactions with digital devices and services, and includes three main subcategories: operating devices, augmenting smart devices, and always available interfaces.

3- Others: Includes a diverse set of application domains, such as enhancing user's perception through embedded sensors or providing sign language translation capabilities.

The insights strongly indicate that multipurpose use is a main functional expectation of this form of robots, so designers should accordingly strive to fulfill use cases that fall within primary and secondary usage domains to create value for daily use. The specifications for primary and secondary use cases are discussed in section 5.1. Moreover, Appendix 1 and Appendix 2 provide numerous use cases from which researchers and designers can use as basis to design and evaluate future robots.

6.3 Interaction Design

6.3.1 Interaction Paradigm

The extracted insights from Orochi and weARable indicate two interaction paradigms serpentine-shaped robotic appendages should partake. The roles are categorized as the following: as *tool*, and as an *agent*. Each role has distinguishing interaction requirements and expectations, and focuses on a different set of experiences that have implications on the design of the user experience.

1- *As a tool*: serpentine-shaped robotic appendages act as an augmentation interface to enable physical and digital interactions with the real world. In this mode, explicit interactions are a major expectation (as discussed in section 4.2.9), where such interaction methods rely on the users to initiate and control the experience. (Hussain, Spagnoletti et al. 2016)

2- *As an agent:* serpentine-shaped robotic appendages are expected to be highly intelligent and autonomous, initiating various actions with minimal or without user intervention.

Therefore, implicit interactions are a major expectation of this mode (as discussed in section 4.2.9), where user intentions, actions and contexts can be indirectly inferred and understood by the serpentine-shaped robotic appendages.

The implications of designing the user experience by each of the paradigm is discussed within each of the next subsections.

6.3.2 Level of Autonomy

The level of autonomy is an important factor to consider when designing interaction, as it designates the user's level of involvement within the interactive experience. Previous efforts in automation (Endsley and Kaber 1999, Beer, Fisk et al. 2014) proposed frameworks to classify the levels of autonomy. Most notably, Endsley and Kaber (Endsley and Kaber 1999) proposed ten levels of autonomy, each with varied user involvement. In lower autonomy modes, the user is highly involved in control and feedback throughout the user experience. In higher autonomy modes, the user is minimally involved within the interaction experience, while full autonomous systems can independently act without user involvement.

The before-mentioned interaction paradigms reflect various levels and expectations of autonomy. For example, *as a tool*, evidence from our studies show that users expects explicit and high level of control over the robot actions. In such mode, the appendage's actions are essentially user initiated and they reflect user interaction intentions. Accordingly, these aspects generally indicate low level of autonomy for the interaction experience, as the user is involved in initiating and ensuring proper execution of the actions. In contrary, *as an agent*, serpentine-shaped robotic appendages are expected to be highly independent from the user, exhibiting implicit interactions, and thereby high level of autonomy. In this mode, the interactions of the robot are automatically initiated and executed with minimal user intervention.

Designating the level of autonomy for each task is important for designing effective user experiences. In our case studies, we designed experiences that reflect three levels of autonomy. First, through Orochi, we designed a smartphone application that offered explicit control over Orochi's servomotors, enabling users to manually control Orochi to carry out physical manipulations. In weARable, we design a serpentine-shaped robotic appendage so that it offers assisted manipulation abilities, allowing users to initiate the action, yet allowing the robot to execute the action without user intervention. Additionally, weARable demonstrated how context awareness can be achieved through sensor information fed from the HMD, which can be used to offer highly autonomous and implicit robotic experiences to manipulate physical objects or to deliver haptic feedback. Therefore, enabling such wearables to act *as agents* with high independency from the users.

6.3.3 Interaction Modality

Upon considering which paradigm the interaction should undertake and the desired level of autonomy, designers should consider the modality of interaction with the robot that correctly corresponds to the target task and interaction paradigm. Based on the interaction paradigm and level of autonomy, three classes of interaction modalities are presented:

1- *As a tool:* Within physical interactions, control methods with *high degree of freedoms (DOF)* are required for enabling robust control over the robot. For example, previous works have proposed using synergetic controls based on user's muscle (Hussain, Spagnoletti et al. 2016, Leigh and Maes 2016) or passing control to the user's legs (Saraiji, Sasaki et al. 2018), or buttons (Hussain, Salvietti et al. 2016). These control methods provide thorough user-controllability with lower levels of autonomy during physical manipulations. Within digital interactions, serpentine-shaped robotic appendages can act as a mean to enable interactions with digital entities. Such scenario constitutes a variety

of interaction experiences, such as always available interfaces for various devices, haptic input and feedback device, digital entity physicalizing and tangible user interfaces (Signer, Ebrahimi et al. 2018). In this mode, serpentine-shaped robotic appendages embody digital entities and provides a physical representation of the intangible digital world.

2- *As an agent: Anthropomorphic Interaction methods* is a category of interactions which constitutes human-like interaction modalities, similar to those found within human-human interactions (Fink 2012, Lemaignan, Fink et al. 2014). For example, using eye gaze to indicate interaction intention with an object, or voice communication similar to conversational robots (Fink 2012, Kashiwabara, Osawa et al. 2012), or automatically pushing the user's hands away from a dangerous object (Leigh, Parekh et al. 2017, Yuhan Bin, Sangwon Leigh et al. 2017). Overall, these interaction cues enable high-level of implicitness in conveying intended actions and objectives to the wearable robot (Schmidt 2000).

Designating the suitable modality for interacting with a serpentine-shaped robotic appendage largely depends on the target task (physical manipulations or digital interactions) as well as the selected interaction paradigm and level of autonomy. Determining each of the mentioned dimensions enables designers to select appropriate interaction modalities to fulfil desired user experience.

6.4   Wearability and Ergonomics

Wearability and ergonomics present an essential design factor of any wearable system. Designing a wearable that is light weight and good comfort enables adoption and usability throughout the day, which are fundamental factors for designing any wearable system (Gemperle, Kasabach et al. 1998, Starner 2001, Schneegass, Mayer et al. 2015, Kotz 2017, Zeagler 2017). As wearable devices, serpentine-shaped robotic appendages should comply with the above basic requirements of wearable systems. Additionally, comprising robotic components and sensors in a snake-shaped form factor raise a number of wearability challenges for serpentine-shaped robotic appendages. Accordingly, our evaluation results revealed a number of insights wearability and ergonomics that are specific to serpentine-shaped robotic appendages. We summarize and discuss within the following subsections.

6.4.1   Attachment paradigm and location

An attachment paradigm refers to the level of flexibility offered by the wearable to be attached to different body locations. Throughout the case studies, a variety of mechanisms are displayed to achieve varied levels of attachment flexibility. First, attachments with minimal flexibility. A good example of this paradigm is in the HapticSnakes system, where the robot is specifically designed to be worn around the waist, whether on front or on the back torso. A slightly higher level of flexibility, which we call *semi-dynamic*, allows the robot to be worn in multiple body locations that are pre-designated by designers. For example, weARable is designed to be worn on the wrist with four different configurations, left or right wrists, facing the inside or the outside. Lastly, a dynamic attachment paradigm allows a serpentine-shaped robotic appendage to be worn in a wide variety of configurations. Orochi offers very high flexibility in the attachment paradigm, as it is designed to be worn and used in many different ways by utilizing its limber body.

Accordingly, the attachment paradigm effects the possible worn locations. Designers should consider where the robot is going to be worn, as this dimensions directly effects the accessible workspace of a robot. For example, minimal flexibility requires an attachment method and planning based on specific body locations where the interaction is going to take

place. Highly-flexible attachment paradigms additionally require further considerations about the body locations the robot is going to carry out the interactions at.

6.4.2 Easily Worn and Taken-Off

Although it may be considered a given factor in modern wearable systems, we emphasize such consideration as the majority of related works in wearable robots do not consider such factor. Unlike modern wearable systems like smartwatches or HMDs, most of the previous works have shown that such robots are not easily affixed to the user's body due to heaviness of the robots or for using numerous straps, thereby requiring more than one person to affix the robot (Llorens-Bonilla, Parietti et al. 2012, Bonilla and Asada 2014). The process of taking off the robot is equally difficult as users have to unwrap various straps and while holding the robot to ensure it does not fall.

A robot worn daily should be quickly affixed to the user without the need for help from other people, similar to general smartwatches or head-mounted displays. Designers should also take into consideration the method of attachment that fulfils such factor. In the next section (Section 6.6.3), we demonstrate some attachment methods that were utilized in the case studies to fulfil such requirements, namely by mounting the robot on a *vest*, using a flexible wrist-worn *bracelet base*, or by using *wrapping mechanisms* through the robot's body.

6.5 Unobtrusiveness and Social Acceptability

Unobtrusiveness is an essential design factor to consider when designing wearables (Dobbelstein, Hock et al. 2015, Profita, Farrow et al. 2015, Profita 2016). Accordingly, evaluation results, especially in Orochi, confirm the importance of such factor. However, our results indicate that unobtrusiveness is varied between when the robot is actively being used and when it is retracted. Addressing obtrusiveness challenges during public use encompass interconnected social and cultural challenges that should be addressed within future works, and they are accordingly discussed in section 7.2. The scope of this design consideration is to encourage designers to consider the methods of reducing obtrusiveness when the robot is retracted, which encompass aesthetic and shape related aspects. These methods are as follows:

6.5.1 Resembling Garments or Accessories

Coupling functional and aesthetic factors is an established method to decrease the social pressure associated with wearables (Profita, Farrow et al. 2015, Profita 2016, Al-Sada, Hoglund et al. 2019). Therefore, this design factor was extended, embodied and evaluated in Orochi. The results of Orochi's evaluation indicate an overall positive impression regarding such factor, and it was shown that such methodology to reduce unobtrusiveness had positively contributed to reducing Orochi's noticeability when retracted. Therefore, designers should consider how their proposed robotic designs should resemble garments or accessories in order to reduce the associated undesired attention.

Resembling a garment comprises two main aspects. First, the robot should aesthetically look like a garment. Second, the wearable should be worn like targeted garment or accessory. For example, a serpentine-shaped robotic appendage can be designed to resemble common accessories, such a backpack (Saraiji, Sasaki et al. 2018, Saraiji, Sasaki et al. 2018) where it can be colored and worn accordingly to closely resemble a common backpack. A serpentine-shaped robotic appendage can also resemble an accessory, like a belt or bracelet (as in weARable) both in terms of shape and aesthetics.

6.5.2   Retractability

The ability of a serpentine-shaped robotic appendages to retract, fold-away or taken-off when not in use is a critical design consideration. Serpentine-shaped robotic appendages are designed to interact within various daily contexts, yet they are not designed for interaction in all contexts and situations. When not needed, a serpentine-shaped robotic appendage should not protrude from the user's body, as it may cause potential hazards when colliding with objects and can draw undesired attention. Moreover, the evaluation results of Orochi indicate that there is a correlation between the posture of Orochi and unobtrusiveness, where the robot was found to be most obtrusive when used and extended from the user's body. Therefore, a serpentine-shaped robotic appendage should be designed in a way so that it does not protrude from the user's body when not in use.

Another important consideration is retractable end effectors. Orochi's evaluation results indicate that Orochi's large and visible end effectors were among the factors that contributed to its obtrusiveness. Therefore, it is highly recommended that future designs attempt to improve upon our case studies through retractable end effectors.

6.5.3   Interaction Acceptability Evaluations

Researchers and designers should consider the acceptability of various digital and physical interactions, both from the standpoints of users and society. The preliminary studies have partially indicated there could be societal aspects in the acceptability of using serpentine-shaped robotic appendages. Orochi's evaluations also indicated that the opinions of others and how common this form of robots are affects users' adoptions. Therefore, future research should consider and evaluate social acceptance prior to deployment, such as by using surveys or user studies.

From a user's standpoint, a wearable's interaction could have varied individual acceptability factors. For example, various participants indicated that Orochi should not be used in certain scenarios, such as when handling babies or shaking other people's hands. However, there was not a consensus on such acceptability; we believe that social and cultural dimensions, that may vary by person, have played a role in determining such acceptability. This aspect is also emphasized in HapticSerpent, where there were numerous researches about haptic feedback, yet actual acceptability of receiving haptic feedback through a robot is largely dependent on the location and type of delivered feedback.

In conclusion, designers, researchers and practitioners should investigate the acceptability of physical and digital interactions, considering both user and social acceptance aspects within each interaction scenario. The general acceptability of novel devices could be affected by cultural or individual motivations that are difficult to identify through simple analysis of previous research literatures. In our case studies, we utilized focus groups and surveying methods to understand the social and user acceptability of physical and digital interactions, respectively. Such knowledge is essential to design serpentine-shaped robotic appendages that people accept and use for daily interactions, and future work should build upon such knowledge to deepen our understanding of this essential challenge.

6.6   The Embodiment and Implementation of the Design Considerations

6.6.1   Designing Serpentine-Shaped Robotic Appendages for Multipurpose Use

Our developed case studies have provided various evidence for the importance of multipurpose use. This section demonstrates some of the methods on how multipurpose use

can be embodied in snake-like robotic appendages. Although some of the presented methods are discussed and presented in general robotic research, these insights are not discussed or embodied within the domain of multipurpose wearable robots, and especially snake-shaped robotic appendages. Therefore, this section attempts to highlight the importance of various methods which can be used by designers to extend the purpose domain of wearable robotic appendage. These insights are classified and discussed as follows:

1- *Embedding Multiple and Varied End Effectors:* Many existing wearable robots mainly embodied anthropomorphic hands or task specific end effectors that are mainly optimized for physical interactions (e.g. (Llorens-Bonilla, Parietti et al. 2012, Chadalavada, Andreasson et al. 2015, Seo, Shin et al. 2016, Rosen, Whitney et al. 2017, Vatsal and Hoffman 2017). In contrary, embedding varied types of end-effectors can enable the robot to accomplish a wide domain of varied physical and digital tasks. Combining multiple types of end effectors allows the wearable to be applicable to different contexts of use.

As shown in Figure 56, Orochi was designed with two types of end effectors, a tentacle end effector with seven DOF, and a serial gripper. The tentacle end effector allows Orochi to carry out physical manipulations requiring dexterity, such as clicking buttons, flipping switches or swiping a smartphone's screen. The same end effector also allows it to be an affective haptic or shape-changing interaction medium, as the high DOF also allows the end-effector is suitable for expressing different signs, or to deliver taps. Similarly, the serial gripper is stronger, allowing Orochi to hold and manipulate objects heavier objects. Therefore, the variety of end effectors enable Orochi to be highly multipurpose. Therefore, serpentine-shaped robotic appendages may be designed with multiple end effector types, making them highly multipurpose in a similar fashion to Orochi.

2- *Changeable end effectors:* Adapting the serpentine-shaped robotic appendages to different daily contexts by using a variety of end effectors is an interesting concept that we also demonstrated with Orochi. By using different end effectors, such as a smartphone holder or a double tentacle, Orochi can accomplish more tasks (Figure 56). The smartphone end effector enables a wide-range of cross-device experiences with the smartphone, such as to use the smartphone for controlling Orochi, or to equip Orochi with smartphone capabilities like authentication and context awareness. Similarly, the double tentacle enables advance object manipulations, such as those shown in previous works on anthropomorphic robotic hands (Funabashi, Yan et al. 2019).

3- *Multifunctional end effectors:* Another method of achieving multipurpose purposes is through multifunctional end effectors. This category of end effectors can comprise a number of sub end effectors which can be used for a variety of purposes. This concept is demonstrated in the HapticSnakes system, where the HapticHydra included a multifunctional end effector that is capable of a wide variety of interactive experiences (Figure 57). Similarly, future wearable systems may embed different types of retractable end effectors that can be used as needed.

4- *Wearability by context:* By wearing the serpentine-shaped robotic appendages in different poses and body-locations, the robot can be utilized for in more applications. We demonstrated this concept throughout the case studies. For example, since Orochi can be used in many different ways, users can use it to virtually extend a limb to interact physically from almost any location around the body. WeARable also reflects this aspect, as it can be worn on the left or right hands, inside or outside of the hand, allowing users to move the interactive space of the appendage based on their contextual needs. Insights about *Wearability* on is discussed within section 6.4.
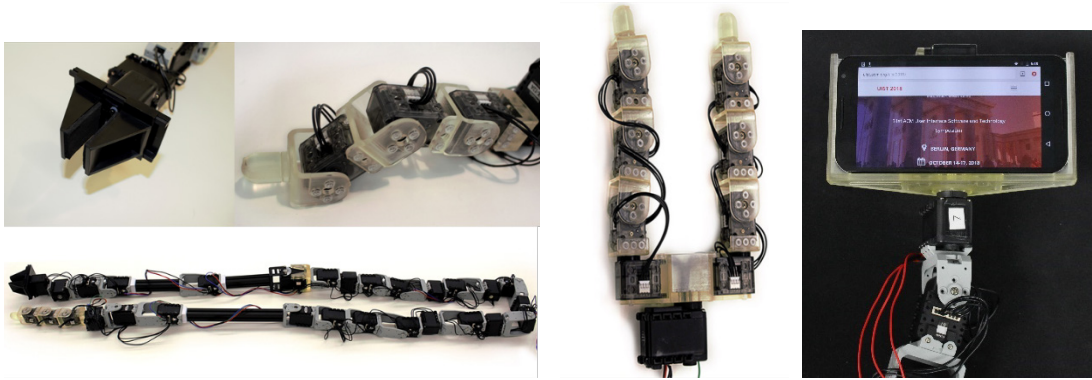
Figure 56 This diagram shows various methods of implementing multipurpose use in the case studies

Figure 57 integrating multiple types of sub-end effectors can contribute to increasing the robot's uses

Future works my attempt to adopt one or more methods to increase the usability of an appendages in multiple domains. Overall, we conclude that multipurpose use is an established requirement and expectation of serpentine-shaped robotic appendages. This section provided an overview of the importance of embodying this design consideration in serpentine-shaped robotic appendages. Moreover, our case studies demonstrated how this design consideration can be embodied by providing various implementations that contributed to increasing the purpose domain of our case studies.

6.6.2 Designing Interaction Experiences for Serpentine-Shaped Robotic Appendages

In order to facilitate designing interactive experiences for serpentine-shaped robotic appendages, we extract and propose the design process that combines the previously discussed dimensions (shown in Figure 58). To utilize this process, designers should first decide the *1) task domain* (as explained in section 5.1 and 6.2). Next, the *2) interaction paradigm* should be determined based on the intended interaction experience designers seek to deliver. As discussed before, selecting the interaction paradigm has specific implications on the user experience design, affecting the corresponding *3) level of autonomy* and suitable *4) interaction modalities*. In the below paragraphs, examples are given on how to design the interaction experience, providing examples from the implemented case studies on how to embody the dimensions.

As presented in Figure 58, each task can accomplish either by the agent or tool paradigms (discussed in section 4.4.4.1). For example, as an agent. weARable can execute various haptic and shape-shifting experiences that are coupled with verbal and visual cues to

resemble a companion robot. These interaction experiences can be initiated by digital services, (e.g. delivering notifications or as tangible interfaces (Fortmann, Root et al. 2016)), or to be driven by context (Leigh and Maes 2016). Example scenarios include delivering haptic or shape-changing feedbacks to draw the user's attention to different events, like incoming messages or drawing attention to dangerous objects. Further works have demonstrated similar scenarios using physical manipulations (Leigh, Parekh et al. 2017).

As a tool, the user can be engaged explicitly within the interaction experience, for example, to manually control the serpentine-shaped robotic appendages DOFs and end effectors to pick up an object. In such scenario, there are not any requirements in terms of autonomy as the serpentine-shaped robotic appendages is fully controlled by the serpentine-shaped robotic appendages during task execution. An example implementation is demonstrated in Orochi, where we utilized a smartphone application that enables users to control the robot's servomotor to manually execute any desired task.

Since the level of autonomy presents a spectrum (Endsley and Kaber 1999, Beer, Fisk et al. 2014), any task can be executed with different levels of autonomy. We demonstrated a semi-autonomous interaction in weARable, where users can select which object to pick up and the appendage can execute the rest of the task without user intervention. In this scenario, the user is only involved to initiate and select which object to pick up, thereby relieving the user from the robot motion task planning and execution specifics. Designing for such level of autonomy requires using *hybrid interaction methods*, which should be determined based on the task specifications and desired level of user involvement within the designed autonomy for each task (Endsley and Kaber 1999, Beer, Fisk et al. 2014, Leigh, Agrawal et al. 2018).
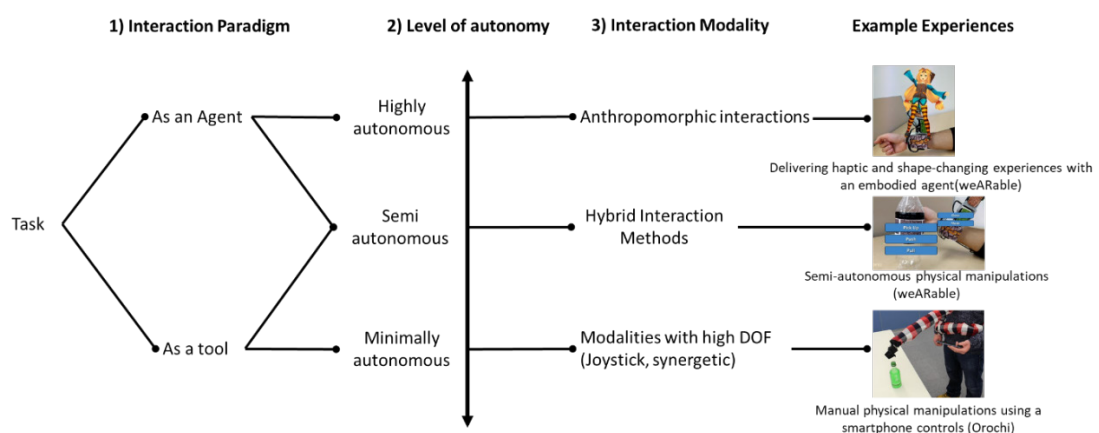
Figure 58 A proposed process to design user experiences.

6.6.3 Designing serpentine-shaped robotic appendages with Wearability and Ergonomics Considerations

Throughout the developed case studies, a variety wearability mechanisms reflecting different levels of attachment paradigms and locations are demonstrated. In the HapticSnakes, the robot is essentially designed for delivering haptic feedback to the front and back torso. Therefore, it utilizes a minimally flexible attachment paradigm, with a placement on the user's waist by using *a vest* that can easily be worn and taken off.

weARable is designed with a semi-flexible attachment paradigm, where it can be worn in a limited set of configurations. Moreover, the robot is able to retract and fold around the user's wrist when not needed. To achieve this, the robot was mounted on a *flexible bracelet base*, which offers good amount of comfort, fit for various users, and can easily be worn or

taken off. Lastly, Orochi provides represents a highly dynamic attachment paradigm, with its flexible body that can be worn in many ways. Orochi's limber body allows it to retract in various postures when not needed, resembling garments or accessories. Also, we used Orochi limber structure as an attachment mechanism, enabling the robot to be worn with many postures and configurations.
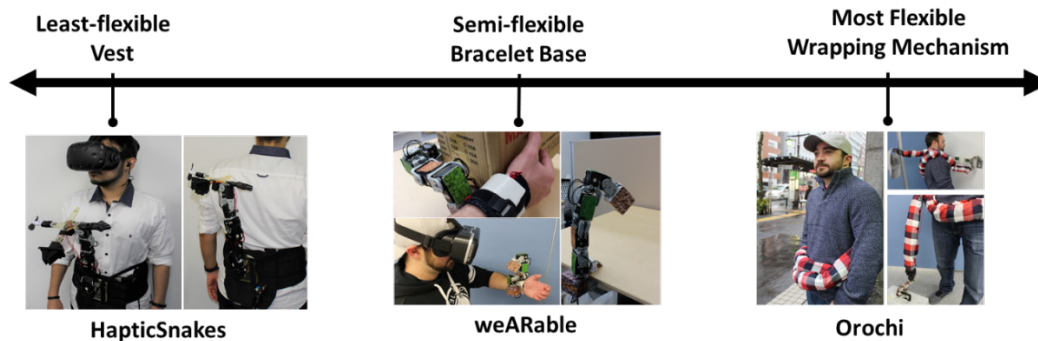
Figure 59 Various methods of implementing wearabiloity mechanisms with varied flexibility

6.6.4 Designing Unobtrusive and Socially Acceptable Serpentine-Shaped Robotic Appendages

The case studies provide a number of examples on how we embodied unobtrusiveness and social acceptability. In Orochi, we covered the robot with two layers, which contributed to its comfort and enabled it to resemble garments. In combination with Orochi's flexible structure, Orochi could both resemble a garment both in terms of its aesthetics and shape. Orochi's flexible design also allows the wearable to be retracted in a variety of ways (Figure 60). Likewise, weARable embodies these design considerations in a small scale. WeARable is covered with colored patterns which double as both fiducial markers and to reduce obtrusiveness. WeARable is also designed to wrap around the user's wrist, thereby enabling it to resemble a bracelet. The combination of these factors allows both Orochi and weARable to be worn in public while drawing minimal amount of undesired attention. Advancements in the shape-shifting and modular robotics can also enable novel designs that would allow higher resemblance to accessories or garments, going beyond our implementations. Such advancements would further contribute to enhanced designs that further address unobtrusiveness challenges.

Similarly, understanding the acceptability of interactions is a critical aspect of usability. In our case studies, we utilized a variety of methods to validate social acceptability. First, in the focus groups, participants where shown Orochi and specifically asked which scenarios they would prefer or would not prefer to use Orochi in. Participants also raised several controversial scenarios, such as those related to human-human interactions. Additional evaluation methods, such as surveys, can be employed to study the acceptability of interactions. In the HapticSnakes, we asked participants to rate the acceptability of receiving feedback with respect various body regions. Such methodology allowed improving our HapticSnakes system and focus its haptic feedback capabilities toward highly acceptable body-regions. Therefore, future research can utilize varied methods to study interaction acceptability (Koelle, Kranz et al. 2015).

Figure 60 Methods of decreasing obtrusiveness based on our case studies

6.6.5 Structural Flexibility and Fulfilment of the Design Considerations

While implementing multipurpose use is an essential consideration of daily worn serpentine-shaped robotic appendages, there exists a trade-off between the structural flexibility and multipurpose use. Having high DOF generally is proportional to the ability of a robot to be highly flexible, which in turn allows higher fulfillment of the design considerations in general and especially multipurpose use. However, within the scope of an implementation using servomotors, we identify a number of shortcomings to having high DOF, which are the following:

1- *Degraded load capacity and efficiency:* designing serpentine-shaped robotic appendages with high DOFs generally degrades the load capacity of the robot. Integrating more servomotors in the joints results in higher flexibility, yet drastically increases its weight, and accordingly decreases the lifting load capacity of the robot when lifting objects using the shoulder servomotors.

2- *Degraded efficiency:* A highly flexible serpentine-shaped robotic appendage may integrate a high number of servomotors, yet, such servomotors are not always used. In many cases, such servomotors are locked to a certain pose (e.g. when retracted). However, these servomotors continuously draw power even when not in use, thereby degrading the longevity of the robot's usage throughout the day.

3- *Heavier Weight:* Increasing DOFs results in increasing the number of servomotors, which contributes to even heavier serpentine-shaped robotic appendages. Decreasing the weight of the robots is generally desirable for a daily worn robot.

4- *Lower Reliability:* Higher flexibility corresponds to more servomotors and components, which makes the system generally more prone to various types of malfunctions. For example, since the robot is snake-shaped, a singular failure in a servomotor or extruded bracket may result in total malfunction of the serpentine-shaped robotic appendages.

5- *Complicated Controls:* Higher DOF has proportional effect on the controllability of the robot. The higher DOFs, the more complex control methods are needed to manipulate the robot, especially with lower autonomy levels. In our implementations, we utilized inverse-kinematic solver to calculate the positions of joint angles, where computational resources are proportional to the complexity of the robot, especially in terms of DOFs.

Compared to traditional anthropomorphic robot arms, there exist a number of advantages of the snake-shaped robots. In one hand, with increased DOFs, the robot is capable of partaking numerous shapes. Such flexibility allows the robot better fulfill requirements like unobtrusiveness in public and wearability by context. In the other hand, having high redundancy (high DOFs) yields degraded efficiency. Standard anthropomorphic robot arms are task optimized, where they are usually equipped with strong shoulder motors and hand-like end-effectors comprising approximately 7 DOFs per arm. To match such

efficiency, we carried out a similar optimization with Orochi (section 4.2) to increase its lifting and holding capabilities during physical manipulations. Therefore, we believe applying structural optimizations to the snake-morphology, such as those done in Orochi, should be done to improve the robot's physical manipulation capacities.

End-effectors comprise an important part of physical manipulations, and having an anthropomorphic end-effector (resembling a human hand) could be efficient for day-to-day interactions. However, most existing anthropomorphic hands, that are designed based on servomotors, are heavy ((e.g. Allegro Hand weighs 1.8 kg (Allegro-Hand 2019)), and requires sophisticated controls for each finger. Therefore, these robotic hands are difficult to integrate for a wearable robot because of their weight. We believe that developing end-effectors based on tendon or cable based structures are much more efficient for daily manipulations (Kaneko, Wada et al. 1991) as they have the dexterity and enough force to execute everyday physical manipulations. Both anthropomorphic and tentacle-shaped end-effectors can be efficient for daily use, yet the selection of end-effectors should be mainly based on the designated task domain.

Despite potential disadvantages for deployment in serpentine-shaped robotic appendages with high DOFs, the use of servomotors has numerous advantages. Servomotors are generally robust, requiring little maintenance and provide generally prolonged usage. They are also widely available in multiple specifications, such as torques, speeds and sizes. Lastly, constructing a serpentine-shaped robotic appendage based on servomotor is a rapid process, as there are an abundance of types and control infrastructures that can be used to power such motors. Lastly, they are easy to maintain and cost effective. Therefore, we chose a variety of servomotor types, where some were industrial-grade servomotors, which enabled us to construct relatively robust prototypes. However, to overcome the disadvantages of using servomotors, other actuation methods and mechanical designs should be investigated. Therefore, we discuss potential technologies for use in developing future serpentine-shaped robotic appendages that can overcome the mentioned shortcoming of servomotors in section 7.6.

Figure 61 trade-offs with relation of DOFs. Based on our the case studies that were implemented using servomotors, the higher DOFs, the more prone a wearable to various trade-offs.

6.6.6 Implications of Autonomy and Context Awareness on the Design and implementation of serpentine-shaped robotic appendages

Our evaluation results indicated that participants had two main interaction paradigms when interacting with serpentine-shaped robotic appendages, *as a tool* and *as an agent*. Overall, participants expect high level of implicitness, autonomy and independence in a variety of scenarios where a serpentine-shaped robotic appendage resembles a companion or an agent. From an implementation perspective, attaining higher level of intelligence has proportional implications on various aspects of the hardware and resources to achieve such expectation.

As discussed by Schmidt (Schmidt 2000), implicit interactions require awareness of the surrounding contexts, so that a system can take initiative in executing tasks without user initiation. Overall, context awareness is a critical requirement for achieving high intelligence within robotics in general (Pichler, Bodenhofer et al. 2004). Numerous research literatures in robotics construct Machine-Learning (ML) systems based on different sensory information, such as RGB-D cameras or tactile sensors, where such information combined and used for object identification, grasping and various manipulations. In the case studies, we utilized three main levels of context awareness and autonomy levels. In the following points, the implication of each level is discussed within the scope of implementation resources, namely computational-power requirements and sensorization:

1- The first control scheme was developed using a smartphone to control Orochi, which offered minimal level of autonomy and context awareness. The control scheme completely relies on the user for context-awareness, and Orochi executes all user commands regardless of efficiency. This scheme is shown on the left side of Figure 62, and since it offers very low context awareness and autonomy, it requires the minimal amount of resources in terms of sensors, or computational-power.

2- Outside-in tracking methods was used to achieve a moderate level of context awareness in HapticSnakes and weARable, where an external tracking system and an HMD based fiducial marker tracking was used, respectively. In weARable, the fusion of the HMDs sensory systems and the robotic appendage provided various intriguing potentials, especially from a context-awareness perspective. For example, weARable could utilize tracking information from the HMD to identify objects, calculate their location with respect to the robot's location and to select which actions to execute on selected object (e.g. grasping, pushing…etc). Such calculations were completely carried out in real-time on the HMD. Realistically, modern HMDs like Hololens (Microsoft 2019) can be used in such scenario, where they already embed a variety of computationally powerful CPUs and power-optimized sensors, which can be used to extend the context awareness capabilities robotic appendages. The shortcoming of this approach is that the system requires constant wireless network connectivity between the robotic appendage and the HMD, thereby limiting the robotic-appendage's independence to sense and identify context by itself. This approach requires a very feasible amount of resources, as the serpentine-shaped robotic appendage can rely on the HMD to achieve an acceptable level of context-awareness and autonomy. This scheme is shown in the middle of Figure 62.

3- High level of context awareness and autonomy have the highest demand in terms of computational power and embedded sensors, which are required correctly identify the environment and execute various actions. Orochi demonstrated how fully autonomous interactions can be carried out. However, future implementation requires a variety of sensors to be embedded so that they provide inside-out tracking and computational-capabilities. For example, Orochi can be equipped with extra RGB-D cameras or tactile sensors to assist in manipulating objects, similar to previous works (Nguyen, Kanoulas et al. 2016, Funabashi, Yan et al. 2019). Higher levels of context awareness and autonomy also have proportionally high cost on the computational resources. For example, various research literatures (Funabashi, Schmitz et al. 2015, Nguyen, Kanoulas et al. 2016, Funabashi, Yan et al. 2019) utilize top of the line graphics processing unit (GPU) to perform complex ML calculations (e.g. NVIDIA GeForce 1080 Titan). Such complex calculations are difficult to carry out in current robotic systems, since these GPUs require desktop systems (Nguyen, Kanoulas et al. 2016, Funabashi, Yan et al. 2019). Currently, such set-ups are very resource intensive and provide low power efficiency, making them difficult to integrate in current-generation robotic appendages. However, rapid developments in technology, such as the introduction of embedded GPU processing within power efficient systems (e.g.

NVIDIA Jetson Nano and Xavier developer Kits (NVIDIA 2019, NVIDIA 2019)), provide intriguing and realistic feasibility for embedding existing methods in future implementations.

Overall, there exists an obvious implication of attaining higher levels of autonomy and context awareness on the hardware design and required computational-resources. These trade-offs where briefly discussed in light of resources required to realize each autonomy or context awareness levels. We believe that current technology is mature enough to provide a moderate level of context-aware and autonomous user experience, which we briefly demonstrated throughout weARable and HapticSnakes design spaces. Realizing serpentine-shaped robotic appendages with high levels of context-awareness and semi-complete autonomy presents numerous research challenge, which we briefly discuss in section 7.8.
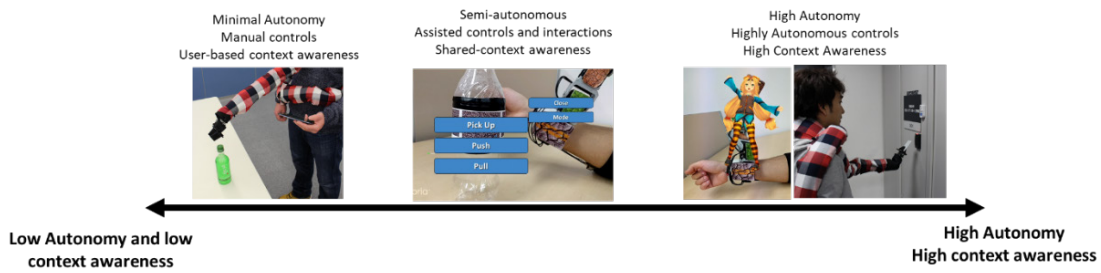
Figure 62 Trade-offs between Autonomy/context Awareness and Implementation complexity

Chapter 7 Limitations and Future Work

We discuss a variety of insights and results from the design and evaluations of our case studies, yet our results have a number of limitations. In this section, we discuss the primary limitations and future work directions. First, although this dissertation identified the main interaction expectations domains, the approach toward realizing serpentine-robotic limbs is mainly utilitarian. There are further domains of interaction that requires further investigations, which are discussed in section 7.1. In addition, social acceptance presents numerous challenges for realizing serpentine-shaped robotic limbs, where this dissertation partially identifies and addresses them. We discuss these factors as well as methods to build upon the presented results in section 7.2. Moreover, the generalizability of the presented design considerations largely depends on the implementations and technology used. Specifically, as this research emphasized the serpentine morphology, evaluating robots with different morphologies, actuation methods or mechanical designs could yield different results. Therefore, the applicability and generalizability of the design considerations is discussed in section 7.3. Section 7.4 discusses potential psychophysical implications that may arise from constant usability of serpentine-shaped robotic limbs, especially as existing works do not address potential ramifications on innate physical human capabilities.

The remaining subsections discuss a number of technical domains required for realizing serpentine-shaped robotic limbs. First, the development of considerations for technical implementation of serpentine-shared robotic limbs is identified and discussed in section 7.5. Technical considerations should comprise technical design dimensions that map to our previously presented design considerations. Actuation methods, mechanical design, and sensorization are discussed in section 7.6, where future work should focus efforts on investigating lighter structures to realize the before-mentioned design considerations. Safety (section 7.7) also presents a challenging aspect to realize this form of wearables, as current designs pose various forms of potential dangers during daily use. Finally, aspects related to the overall realization of serpentine-shaped robotic appendages are discussed in section 7.8, where we highlight which forms of serpentine-shaped robotic appendages and interaction domains are feasible for short-term or long-term implementations.

7.1 Purpose Domain

The extent of purposes serpentine-shaped robotic appendages can accomplish is broad. Although our conducted work reveals numerous and diverse user-elicited daily scenarios, there exists other use cases that are difficult to elicit with our utilized evaluation methods. For example, hedonic purposes, such as using the appendages as public displays (Colley, Pakanen et al. 2016) or as expressive fashion wearables (Dunne 2010, Wang, Juhlin et al. 2016). Such direction was briefly hinted in the focus group, when one participant mentioned that Orochi represents a "*fashion statement*", and continued to mention that they would wear Orochi to draw attention. In such scenario, Orochi would provide a sense of uniqueness and pride when worn, like the sensations associated with unique and expensive fashion items or jewelry.

Emerging works within wearable robots also provide unique use cases that serpentine-shaped robotic appendages could accomplish. When a serpentine-shaped robotic appendage is controlled by users other than the wearer, the resulting interaction experiences provide intriguing potential for a third interaction paradigm. For example, a serpentine-shaped robotic appendages can be used as a mean for achieving affective haptics, thereby embodying others to deliver nudges, hugs or other means to show affection (Eid and Osman 2016). Likewise, teleoperation (Williams, Tran et al. 2018) or collaborative telexistence (Saraiji, Sasaki et al. 2018) enable the serpentine-shaped robotic appendage to embody remote users in collaborative tasks involving physical or digital entities. We believe such interaction paradigm should deeply be investigated considering the previously presented interaction paradigms (i.e. *as an agent* and *as a tool*).

Which digital functionalities should be embedded with serpentine-shaped robotic appendages? mobile phones have started as devices that enabled messaging and calling on the go, yet they evolved to include various functionalities, such as note taking, photography, media consumption and authentication (similar to prepaid train cards like SUICA (JREast 2019)). Most of such functionalities where not present in earlier phone designs. Similarly, a serpentine-shaped robotic appendage could embed a variety of digital functionalities to replace the reliance on a smartphone. Designating which digital functionalities to embed is a research challenge that we believe requires deeper investigations and much more mature robotic designs that could be used throughout the day.

7.2 Social Acceptability and Public Usage

Although we tackled several challenges of unobtrusiveness and public use, the challenges concerning social acceptability are much broader and interleaved. In this dissertation, we focused on designing serpentine-shaped robotic appendages that drew the minimum amount of attention when worn in public. However, different results were raised when the appendages were actively being used and when worn in ways that do not resemble common garments. These aspects raise challenging aspects regarding public usage.

Future work should extend our evaluations to identify and understand the social acceptability of serpentine-shaped robotic appendages when in use. One direction could be to focus on gauging social acceptance based on culture or gender. For example, a survey could be designed to investigate acceptability of using a serpentine-shaped robotic appendage in various contexts, comparing males and females, or participants from Asia and Europe. Furthermore, Acceptance is not only concerned with the society, but with the users themselves. For example, similar to novel wearables (Profita 2016, Google 2019), wearing robotic appendages in our modern society, where such devices are rare and remain highly

novel, could cause embarrassment. For example, publicly wearing Google Glass (Google 2019) had huge social ramification, like being banned in various locations (Telegraph 2019) or discriminated against and assaulted for wearing it (CNBC 2019). Although substantial efforts have been carried out to study social acceptance of technology in general (Profita 2016, O'Kane, Aliomar et al. 2019, Schwind, Deierlein et al. 2019), addressing social acceptance challenges of wearable robots are in their infancy and requires significant advancements in terms of tools and methodologies. These factors are not fully addressed in this dissertation and should be thoroughly understood through future work.

7.3   Generalization of the Design Considerations and Evaluation Results

The gathered insights from the user studies are essentially a reflection of the attributes of the developed appendages, and essentially the snake morphology. Various disadvantages were discussed based on the efficiency and load capacity related to the redundancy of DOFs within serpentine-shaped robotic appendages. Further limitations are discussed for delivering haptic feedback, which are related appendages that are fixed to a base (similar to HapticSnakes). These shortcomings differ based on the robot design specifics, such as morphology or actuation methods. For example, highly modular robots, soft pneumatic and tendon-based structured (Kaneko, Wada et al. 1991, Yim, Shen et al. 2007, Yao, Niiyama et al. 2013, He, Xu et al. 2015) could provide methods to overcome the disadvantages in the presented case studies, yet have other limitations that may affect the fulfillment of the design considerations. Therefore, the applicability of the design insights and considerations should be investigated within the scope of other robot types, which may have different actuation methods, mechanical designs or structures.

Although the evaluation results and insights may not fully apply to robots with different design attributes, we believe that the design considerations can fundamentally be generalized and therefore applied differently with other morphologies. The key to multipurpose use is adaptability in the serpentine-robotic structure that allows conforming to different contexts. Therefore, research on reconfigurable robots (Yim, Shen et al. 2007) and shape-shifting robots is essential (e.g. snake robots (Hirose and Morishima 1990, Erkmen, Erkmen et al. 2002). The former uses modular designs that can be assembled based on different objectives, and the latter uses hyper-redundant structures (with many DOFs) to adapt to multiple contexts. Our robots reflects this aspect in its flexible design, making it applicable to a wide variety of tasks.

Future work should focus on other designs to achieve multipurpose use. For example, an appendage with a modular body or end effectors can be utilized to extend be used to achieve multipurpose use, as partially shown in Orochi, where we demonstrated a variety of attachable end effectors offering different functionalities. New robot morphologies that are highly modular could also be investigated. Wearability by context and unobtrusiveness are substantial for increasing the appendage's uses and enabling daily wearability across numerous contexts. For example, future work can explore additional means to realize these two considerations. A serpentine-shaped robotic appendage may be designed as a cross body bag, which offers multiple wearability options (front, back, left or right sides) and resembles common wearables. In this example, structural flexibility is also essential; to shape-shift to a bag and to be able to interact when worn in different postures. Therefore, research on reconfigurable and shape-shifting robots should be a starting point explore future formfactors that can conform to the design considerations. Accordingly, our design insights and considerations form a baseline for directing future work towards general fulfillment of main

requirements and expectations of daily use.

Similarly, the requirements and use case distributions, extracted from the preliminary studies and Orochi's evaluations, are valuable resource for designing, refining and gauging future serpentine-shaped robotic appendages against realistic usage expectations and requirements (Angeles and Park 2008). The gathered use-case scenarios can be used to extract functional requirements and to ensure suitability of future appendage-designs for daily use. Moreover, metrics like time-on-task and success rates can be developed based on gathered use cases, where they can be used to validate the performance of an appendages (Appendix 1 and Appendix 2).

7.4 Psychophysical Implications

Previous research on multipurpose SRLs briefly raised various concerns about the effect of SRLs on innate human capabilities (Leigh and Maes 2016). The extended use of a serpentine-shaped robotic appendages for physical manipulation, especially *as a tool*, could have detrimental effects on the human's ability to use their innate capabilities to manipulate physical objects. Despite the mentioned potential drawback, the scarcity of research within this area requires extensive investigation and evaluation of such critical factors.

One of the factors related to SRL usage is body ownership, which is defined as the ability of a person to perceive his/her a body or body part as their own (Maselli and Slater 2013, Chen, Huang et al. 2018). Body ownership has been found to be affected by multiple interleaved factors, ranging from visual and haptic feedback, to control methods, shape and aesthetics of the extra hand (Guterstam, Petkova et al. 2011, Maselli and Slater 2013, Kulu, Vasser et al. 2016). We believe an important research direction is to understand the design requirements and specifications of body ownership with respect to the design dimensions of serpentine-shaped robotic appendages, especially since serpentine-shaped robotic appendages can be used as third arms to physically manipulate objects. Most of previous works evaluated body ownership factors within VR set-ups (Lugrin, Latt et al. 2015, Won, Bailenson et al. 2015, Kulu, Vasser et al. 2016, Kondo, Sugimoto et al. 2018), where the extent of their results' applicability to physical robotic systems is not unknown. Therefore, further research should emphasis evaluations involving robotic appendages, taking into consideration specific serpentine-shaped robotic appendages contextual and usability factors.

At the time of writing this dissertation, the research literatures addressing the effects of extended robotic usage on our innate capabilities are scarce. Specifically, the factors related to body ownership on robotic appendages are in their infancy. Therefore, future work should attempt to explore the potential effects on innate psychophysical capabilities that may arise upon extended usage of such robots. Moreover, an essential research direction is to focus future studies on the design factors, including aesthetic, control and task-related attributes, which may contribute to increasing or decreasing body ownership. Accordingly, the outcomes should be incorporated within the design considerations so that the dimensions contributing to higher or lower body ownership are addressed within the design process of future serpentine-shaped robotic appendages.

7.5 Technical and Implementation Considerations

This dissertation focuses on a UCD approach, thereby attempting to elicit, verify, embody and evaluate user gathered assumptions, requirements and expectations. Although UCD is well-established and crucial for developing novel systems, it's user-centricity could be

limiting; other aspects are not captured, especially technical considerations and implementation insights. For example, in robotics research domains, various research literatures have provided technical frameworks that introduced systematic processes and dimensions for constructing various types of robots (Barnes, Everett et al. 2005, Goodwin and Winfield 2008, Rezazadeh, Abate et al. 2018).

Accordingly, a critical future research direction is to extend the presented design considerations with technical implementation considerations. Efforts in other robotics have presented a variety of frameworks for designing and implementing robots from a technical standpoint. For example, Goodwin and Winfield (Goodwin and Winfield 2008), provided a comprehensive framework for designing and implementing mobile robots from a system perspective. Thus, their work provided a systematic process that offered traceability between various robot functionalities and robotic technical components, such as chassis, power, and communication methods. Nevertheless, to achieve a mature understanding of the technical and implementation considerations of serpentine-shaped robotic appendages, significant efforts should be carried out to explore additional alternative technical implementations to our presented use cases. For example, exploring the use of other actuation methods, mechanical designs and sensors. Similar to previous efforts in constructing frameworks (Goodwin and Winfield 2008, Rezaei, Shekofteh et al. 2008, Rezazadeh, Abate et al. 2018), technical insights can then be extracted from various implementations and analyzed for creating a framework for serpentine-shaped robotic appendages.

7.6   Actuation, Mechanical Designs and Sensorization

Although servomotors are overall powerful and durable, their large form factor, weight and power-consumption are restricting, especially when compared to actuation methods that are advantageous in mentioned traits, like shape-memory alloys (Coelho and Zigelbaum 2011, Roudaut, Karnik et al. 2013) or pneumatic actuators (Yao, Niiyama et al. 2013). Moreover, the suitability of servo motors for the presented use-cases is subjective. While some use cases justify strong active actuators, such as manipulating heavy objects, others do not. For instance, form-factor transformations to accomplish some use cases, like when operating a smartphone (as in Orochi) or an armband (as in weARable), generally do not demand high torques to transform or carry out such tasks. They also do not require continuous actuation to maintain such postures. Therefore, the use of active actuation in these contexts is inefficient and could degrade motors upon extended use.

Overall, as every actuation method has advantages and shortcomings (Coelho and Zigelbaum 2011, Roudaut, Karnik et al. 2013, Yao, Niiyama et al. 2013), actuation requirements of each usage scenario should be reflected on chosen actuation methods, keeping in mind the trade-offs in size, weight, torque and power consumption factors of each actuation method. An important research direction is to develop actuation methods that balance mentioned trade-offs, specifically being lightweight, small in size, power efficient and sustainable for daily wearability. Other aspects include durability of the mechanical components for daily usage contexts, and generated heat upon usage might have implications on comfort, thermal balance and moisture transport (Clear, Morley et al. 2013, Chin 2015). These aspects where not discussed in any surveyed works.

7.7   Safety

Safety is one of the most important aspect of designing wearable robots, yet it is rarely discussed within any of the surveyed research literatures (Llorens-Bonilla, Parietti et al. 2012,

Bonilla and Asada 2014, Wu and Asada 2014, Hussain, Spagnoletti et al. 2016, Leigh and Maes 2016, Tiziani, Hart et al. 2017, Saraiji, Sasaki et al. 2018). As serpentine-shaped robotic appendages comprise high-torque actuators that can damage the user's body or the environment, it is important to take safety into consideration within the mechanical design of such robots. In this section, we summarize a number of safety aspects that should be addressed within future research efforts to realize serpentine-shaped robotic appendages for everyday use.

In our developed case studies, the robots press against the user's body for stabilization during physical manipulations and when retracted. Such aspect poses safety risks, especially in sensitive regions of the bod (e.g. neck, abdomen or fingers). Additional unconsidered aspects in related literature is heat. Continuous use of these robots produces high temperatures, especially when lifting or holding heavy objects. Such aspect should be thoroughly considered. For example, ensuring proper cooling systems are installed and providing proper safety procedures when the motors overheat and malfunction. Lastly, the robot arms could collide with the user's body and cause injury upon use. Therefore, new safety methods are necessary for detecting the user's posture and limb locations to avoid collisions.

Although this dissertation does not thoroughly address safety challenges in designing serpentine-shaped robotic appendages, safety is one of the most fundamental aspects that ensure successful realization, deployment and use within future societies. As a result, future work should address safety aspects from the perspective of serpentine-shaped robotic appendages, in a similar method to the efforts conducted in other robotic domains (Veneman 2017) . Future efforts should focus on identify potential safety hazards when wearing and using serpentine-shaped robotic appendages on daily basis, and accordingly propose methods to address these concerns.

7.8 Realizing Serpentine-Shaped Robotic Appendages

It is feasible to use existing technology to fulfill the design considerations and realize a serpentine-shaped robotic appendage. However, the domain of realization largely depends on the degree of multipurpose use and flexibility of implemented robot. For example, the implemented designs in the HapticSnakes and weARable are functional and efficient in carrying out various tasks. However, highly flexible and multipurpose robotic appendages are difficult to realize without significant research to mature required technologies. In this section we discuss aspects related to the realization of serpentine-shaped robotic appendages within the short term and long-term future.

The design considerations can be used to realize a serpentine-shaped robotic appendage based on current technologies, which can fulfil the minimal requirements needed to fulfil the design considerations. For example, weARable is a highly efficient device and it fulfills the design considerations of serpentine-shaped robotic appendages. WeARable is *multipurpose*, as it can execute various physical manipulations and digital interactions. It is *wearable by context*, as it can be worn on the left or right wrists, facing inwards or outwards. It is *unobtrusive*, as it is able to retract around the wrist, thereby maintaining a relatively low profile, especially if upgraded with smaller and more robust servomotors (e.g. Dynamixel X servomotors (Robotis 2019)). When combined with an unobtrusive modern AR HMD (such as North Focals (North 2019)) or Epson moverio (Moverio 2019), weARable provides an intriguing appendage design with efficient and realistic usage scenarios. Therefore, serpentine-shaped robotic appendages with the scalability of weARable are feasible for development and deployment in the short term.

As envisioned in Orochi, higher fulfillment of the design considerations requires

sophisticated implementations. Designing wearables that are highly multipurpose and highly flexible to be worn in many locations and configurations is very hardware demanding. Essentially, realizing highly multipurpose robots requires highly flexible designs with many DOFs, which is difficult to achieve with off-the-shelf servomotors. Thus, realizing such robots with high scalability require significant research development of alternate actuation methods and mechanical designs that are highly flexible and light in weight (e.g. tendon-based structures). Moreover, as discussed in section 6.3, providing implicit experiences demand high autonomy and context awareness, which accordingly puts further implementation requirements in terms of advanced processing units and sensors. Therefore, realizing a serpentine-shaped robotic appendage that is highly multipurpose, dynamically worn, and offers implicit interactions requires significant research efforts that span multiple research domains.

In conclusion, the realization of serpentine-shaped robotic appendages largely depends on the level of fulfillment of various dimensions in the design considerations. Realizing a serpentine-shaped robotic appendage that is highly multipurpose, dynamically worn and providing implicit interactions require significant research and development in actuation technologies, mechanical design, automation and context awareness. In contrary, realizing a serpentine-shaped robotic appendage with a focused multipurpose domain, semi-flexible wearability, and interaction experiences that do not demand high context awareness or high autonomy is feasible using existing technologies. Accordingly, the latter provides an intriguing and very feasible direction to fulfil the design considerations and realize daily-worn serpentine-shaped robotic appendages.

Chapter 8   Conclusions

This dissertation focused on four main research questions with the overall objective of realizing serpentine-shaped robotic appendages. Addressing these research questions enabled us to make four main contributions:

1. Identification, analysis and classification of daily usage expectations and domains of serpentine-shaped robotic appendages within everyday contexts.

2. Identification of social and user acceptability challenges, and the methods to address and accommodate these challenges and requirements.

3. Design and Implementation of novel user experiences that demonstrate:

    - How cohesive user experience can be designed to enable multipurpose use.

    - Novel user experiences that provide multiple methods of cross-device interactions enabled by serpentine-shaped robotic appendages.

4. Identify and discuss essential domain-specific design considerations to enable researchers and practitioners to design and evaluate serpentine-shaped robotic appendages against user requirements and expectations.

Addressing these research questions contributed to understanding the underlying requirements, expectations and challenges in realizing snake shaped serpentine-shaped robotic appendages from a user centric perspective. This chapter summarizes the contributions of this dissertation with respect to each research question.

This dissertation is a step forward in bridging the knowledge gap in terms of the user expectations as well as usage and design requirements for daily used serpentine-shaped robotic appendages. The first research question is addressed in the preliminary studies and Orochi's study. The results of these user studies provided a comprehensive use case distribution, comprising a numerous user-elicited daily use cases. Accordingly, these use cases were structured and classified, and their distribution was analyzed in order to understand essential use case domains. The results provide both an overall understanding of the interaction expectations, in the form of categorizations, and a comprehensive list of use cases that researchers can utilize as bases for designing and evaluating future serpentine-shaped

robotic appendages. These results are significant contributions to this field; they are the first to provide an overview of the daily usage expectations of wearable robotic appendages, and the first to provide a basis from which design and evaluation criterion can be derived from.

Constructing a daily worn serpentine-shaped robotic appendage encompasses numerous interleaved factors. One of the most important factors is social and user acceptability, which was the main aspect of the second research question. This domain was probed through the design development of Orochi, which reflected an unobtrusive design by resembling a common garment when used. Moreover, Orochi's evaluations provided evidence that such design approach contributes to drawing a minimal amount of undesired attention when worn publicly. Public usability presents further challenges for acceptability, as using a serpentine-shaped robot may not be socially acceptable yet. Therefore, this dissertation highlights this challenge and provides several future research directions to address this problem. The evaluations of HapticSerpent and Orochi also pointed various insights about undesired interactions and unwanted use cases, respectively. These insights about undesired interactions and use cases further complement the user expectations, as future designs should avoid undesired use cases and interactions to achieve high user adoption. Social and user acceptance has not been an emphasis of previous related works in wearable appendages (e.g. (Bonilla and Asada 2014, Wu and Asada 2014, Parietti and Asada 2016, Vatsal and Hoffman 2017)). However, the importance of this domain is well established within HCI wearable systems research that target daily use (Dobbelstein, Hock et al. 2015, Hsieh, Jylh et al. 2016, Profita 2016, Alallah, Neshati et al. 2018, Schwind, Deierlein et al. 2019). Therefore, our results and analysis provide valuable insights towards realizing serpentine-shaped robotic appendages that adhere to social and user acceptance criterion.

Multipurpose nature of daily used serpentine-shaped robotic appendages presents interaction and control challenges that have not been addressed in previous domains. These challenges are raised and addressed in the third research question. Accordingly, this dissertation takes the first step to design, demonstrate, and evaluate a multipurpose user experience presented within weARable's design space (section 4.4). Previous insights from the case studies indicated that users expect to interact with serpentine-shaped appendages under two main paradigms. Therefore, the presented multipurpose user experience also embodies these requirements, first by presenting various experiences that fulfill these two paradigms, as well as demonstrating a mechanism to switch among experiences and interact under each of the paradigms. Furthermore, cross-device experiences, combining serpentine-shaped robotic wearables and digital services or devices, presents an intriguing frontier for future wearable system. Accordingly, we extract insights from various case studies and presents a classification of novel experiences covering three interaction categories: 1) operating other devices, 2) augmenting smart devices, and as 3) always available interfaces. Overall, the extracted insights advance the state-of-the art by providing a cohesive multipurpose interaction experience for daily use, and contributing with a classification of various novel cross-device combining wearable robotic appendages and various digital services and devices.

The fourth research question was addressed through the culmination of the design and implementation of the four case studies and the extracted design insights. The design considerations provide guidelines under four main domains, which are multipurpose use, interaction design, wearability and ergonomics, and unobtrusiveness in public. First, *multipurpose use*, which represents an essential expectation of daily worn serpentine-shaped robotic appendages. Several methods of implementing multipurpose use were presented and thoroughly discussed, citing examples from the developed case studies. Second, *interaction design* emphasized the methodology to construct user interactions based on two main interaction paradigms, autonomy levels, and interaction modalities. An overall process was also presented, enabling designers to construct experiences for each task based on the

presented dimensions.

Third, *wearability and ergonomics*, which presented dimensions concerned with various wearability paradigms and attachment mechanisms. Serpentine-shaped robotic appendages can be designed with varied flexibility in their wearability, ranging from the ability to wear the serpentine-shaped robotic appendage anywhere around the body, to less flexible paradigms targeting specific regions. The difference in selected paradigms also reflects the need for suitable attachment mechanisms to fit such consideration. Therefore, sufficient examples are presented from the case studies that present an embodiment of each presented wearability concept. Fourth, *unobtrusiveness and public use*, which provided recommendations and methods to minimize drawing undesired attention upon wearing serpentine-shaped robotic appendages in public. A variety of methods were presented, mainly resembling common garments in terms of aesthetic and shape, as well retractability. Overall, the design considerations provide both design guidelines and implementation methodologies based on the case studies. Therefore, future designers can utilize the design considerations as basis upon which future daily-used serpentine-shaped robotic appendages can be designed.

Overall, the user-centered research process that is adopted in this thesis enabled establishing an in-depth understanding of the primary factors required to realize serpentine-shaped robotic appendages. The preliminary studies enabled us to extract necessary insights about the general user expectations and requirements, and also professional HCI and robotic perspectives. These results enabled a broad initial understanding of the challenges and opportunities surrounding serpentine-shaped robotic appendages. Accordingly, the case studies are designed, implemented and evaluated for the purpose of probing specific and deeper challenges in realizing this form of wearable systems, where these challenges have not been addressed in any surveyed research literature. Accordingly, we group and analyze extracted insights from the design, implementation and evaluation processes of all the case studies, providing design implications for creating future systems. Moreover, we extend and structure the insights to present a set of design considerations, where design dimensions are discussed, and embodiment methods are presented based on the constructed case studies. These design considerations provide culmination of factors that should be considered in order to realize serpentine-shaped robotic appendages, taking into consideration multi-dimensional factors covering multipurpose use, interaction design, wearability and ergonomics, and social and public use. Therefore, the outcomes of the case studies, as explained above, allowed addressing the research questions through design and implementation insights that realistically addressed the interleaved and varied factors required for daily used wearable systems.

Overall, the flexibility enabled by the numerous DOF within the serpentine morphology provide to be very robust to embody the design considerations. The flexibility of such morphology enabled fulfilling the design considerations in a variety of methods, proportional with the embodied DOF. Therefore, we believe that the case studies provide solid evidence toward of the versatility and robustness of this morphology for use as a base formfactor for wearable systems and to fulfill various design considerations of daily use.

A number of limitations and future research directions are also discussed. Specifically, the generalizability of the considerations should be validated with respect to other implementations (e.g. other robotic morphologies or actuation methods). Further embodiments of the design considerations could overcome the reported shortcomings of the case studies, or present further unexplored methodologies to better fulfil the design considerations. Further challenges also lay in understanding deeper repercussions of using serpentine-shaped robotic appendages in public, as well as investigating additional novel

usability domains like hedonic or fashion purposes. Similarly, the feasibility of implementing wearables based on the presented case studies is discussed, given that the level of fulfillment of the design consideration is relatively scaled down.

8.1 Closing Remarks

This dissertation focuses on the primary research challenges of realizing serpentine-shaped robotic appendages, namely the design methodology and implementation of multipurpose use, interaction design, wearability, unobtrusiveness and acceptability. Accordingly, the extracted insights and design considerations provide the first step in understanding each domain of challenges through a UCD development and evaluation approach. Future designs of serpentine-shaped robotic appendages should extend the presented case studies and explore other means to better fulfil the design considerations through novel robotic designs, interaction methods and wearability mechanics. Unobtrusiveness and acceptance are also a fundamental challenge of any wearable system; thus, it deserves to be thoroughly studied based on the well-established methodologies from wearable computing research.

In conclusion, realizing serpentine-shaped robotic appendages constitute multi-layered interconnected design challenges that this dissertation identified, studied and evaluated. The design considerations emphasized these primary challenges in realizing serpentine-shaped robotic appendages, thereby providing researchers and practitioners with necessary foundation from which future designs can built upon. Realizing small-scale serpentine-shaped robotic appendages is feasible using existing technologies, while larger scale implementations require further research and engineering efforts to realize. We believe this dissertation contributes to realizing daily worn robotic appendages in general, and especially emphasizing serpentine-shaped ones. The principle findings, implementation approaches and design considerations provide a general understanding of how this form of wearable robots may play role in our daily lives, with the hope inspiring and encouraging researchers, practitioners and entrepreneurs to realize daily worn robots in the near future.

Appendix 1: List of Use Cases from Preliminary Studies

Below is the list of use cases gathered from two focus groups conducted in Tokyo and in Germany. The list presents a list of raw data, and thereby can be reclassified, filtered and processed accordingly. Since the entries are based on the analysis of the discussions during the focus groups, the classification, in section 3.1.3.2 SRL Cases of Daily Usage, omits 11 entries due to duplication and reclassification as design requirements rather than use cases.

Protection against falling	Hold object to open a bag	Be as a dryer for blowing hair	Expand a movable range to change a light bulb which could not reach
Holding objects while doing other tasks	Hold object for sewing	Warm as heater when we go outside	Attach a camera for taking picture
Has attachable cameras (Near the end of the device) to enable wearers to see	Hold a nut to tighten a bolt	Electric shock for crime prevention	Protection for slip while walking
Locomotion (Walk faster using the robot)	Hold object for cutting with a saw	Fire a gun for crime prevention	Shield when we attacked by robbery
Hold driving wheel/other stuff while eating (Driving and eating, could be two use cases)	Changeable attachment as mixer	Sense the temperature of food when cooking	Slap for waking up
Grab things that exist in high places	Flying to move faster	Mimic as cat or dog as a tail	Move without waking up
Holding books/notes while walking/eating or other tasks	Treatment of dangerous things	Expansion of athletic ability to take balance by attaching a tail for fighting	Adjusting the direction of a shower head for washing head
additional legs which enable us to sit anywhere	Treatment of dirty things when someone vomit	Emotional expansion without talking by a tail	Hold a hair for hair brushing/drying
enable recovery when losing balance to avoid falling	Detecting air condition	Drive a car when we eat with driving	Cut noodles for support to eat noodle
Help folding clothes while ironing	Sniffing around for detecting pH, temperature, density of oxygen	Hold a baggage with shopping	Hold down paper for writing
Open the door for you while carrying heavy items	Pull outs a weed by cleaning a garden	Froth to make meringue as it is	Walk for you so you wouldn't need to put energy

		an exhausting cooking task	
Help you walk/move while laying down on your back/sleeping	Multitasking (Brushing hair and tooth)	Mix something for cook	Deaf people could hear through it
Replacing your alarm (Waking you up)	Carry things around	Put away dishes or tools that already used while cooking or painting	Can enable you to hear frequencies you do not hear (Sense augmentation)
Juggling	grabbing things	Duet alone to play piano	Sense substitutions for the blind (Similar to current systems)
Hold object	Grab things that are beyond arm's reach	Fighting with three arms for boxing	Warning systems for anything (earthquakes...etc)
Support for specific work (welding, thread cutting)	Complement users' arms who suffer from lost muscle strength (Old people)	Take Care of kids when kids are running away without parents noticing	Like a phone, bring up alarms or others
Move independently	Climb trees	Material arts or Boxing as amusement	For police, checking dangerous people or criminals
pseudo healthy arm when we broke arm	Commuting	Increase a technique for fighting	- Deflect bullets
Long distance move with third or fourth leg	Make a person look higher (leg SRL)	Grabbing surgical tool	Can make diagnosis of people's voice and bio signal and deduct feelings and emotions of other people
Approaching to high place with stretchable legs	Walk faster with larger steps	Keyboard typing	If you fall, it will support you
Grab something with additional finger for foot	Playing different music instruments at the same time in coordinated manner	Hold an umbrella	Bring or have built in glasses
Dancing	shut down monitor when you overwork (Force you to stop working), work management	Reach to an object that is far or high	find glasses when they are lost
Line up the items of the supermarket	Signals directions while biking	Add external power which exceed human's ability	Separate Trash (Segregate plastic, burnable and others) + Hygienic related aspects
Fighting	Stop person from falling while skating	Use as third arm when we can't use both hands	Doing Simultaneous Tasks (Play drums and do other things at the same time)
Duet alone to play piano	Could have a camera integrated to extend human vision	Scrolling the smart phone to see a recipe for cooking	Can become a chair

Hold an umbrella with a crutch	Feel temperatures of things	Flip through the book while eating or cooking	Sit everywhere by a tail
Care kids when kids running away without parents do not realize	Feel chemicals in surrounding objects (to indicate danger, taste...etc).	Replying to email when we are doing the other task	Multi-tasking when we use both hands or legs
Froth something for cook	Used as an instrument for measurement	Sewing	Learn Sign Language and interact with people simultaneously, something like a translator
Open a door while both hands are using	May include other devices (like a smartphone)	Ironing	It adapts like a computer, it is generic, it can be adaptable by the user and personalized too
Hold a surgical tool during surgery	It can write homeworks (and save the handwritten homework) it remembers all the movement made during handwriting	Piano duet	Do all trivial daily tasks (closing the lights, flushing toilet among others)
Typing keyboard	Enable you to feel the environment in the dark (or for blind people)	Take a shower	It can save people in emergency situations (enable wearer to float, breath through the arm)
Martial arts	Biometric sensors to know if you are ill or injured	Hold a paper for writing	Can become an umbrella
Multiple function on hand	Integrate a lamp within the arms to navigate in the dark for example	Support for stretching with both arm simultaneously	Purify water using the embedded functions (Boil sea water, and provide water)
Take something high or far	it can adapt to what you need (you have stick, can become two arms) it folds to one, or becomes a long stick etc	Extend legs for pick something high on kitchen	Check alcohol level and tell you not to drive
Crime prevention	Pick stuff up when they are dropped (Automatically) reaches to the ground and picks them up for you	Extend legs for look something high on kitchen	It can drive the car instead of me
Instruct work procedure by finger or display	if you drop something in tricky places (tight, high or if you drop your phone on the tracks) the device can easily get it safely	Long distance walk or run fast	Check sugar level without withdrawing blood since it is connected already
Look recipe or memo while cooking	Could have some tools integrated (To repair cars for example).	Hold a book for reading when we eat something	Extra quick for typing on the PC

Replying mail or playing game while washing dishes	In a forest, it can act as a sonar to detect movements in the dark (Sense transformation)	Luggage holder when shopping	Type of multiple keyboards on the same time
Talk independently to have fun	Be worn -> leave your body to do something else, then comes back to be worn (Disassemble, do other tasks and then assemble again)	Tickle the other's side in lab for make someone laugh	Can listen to many people speaking, segregate what they say and filter it then provide it to the user
Electric shock for crime prevention	Integrate a clock to tell time	See invisible place to take something in shelf as endoscope	sense the burger if it is well done or ready to eat
To hit a gun for crime prevention	Waiters can carry and serve more stuff in restaurants	Put up an umbrella when we are walking with a crutch	Pet animals (Without the fear of being bit)
Instead of mixer	When sneezing, it will grab the tissue and cover your nose automatically.	Prosthesis when we injured foot or arm	Cool or heat your body down in hot temperatures
Detect temperature of food	Shake hands with women using SRLs (Cultural and Religious Reasons)	Slip prevention	Figure out perfect posture while sitting (Upright sitting, or hold you to sit on air…etc)
Instead of dryer to dry hair	Adapt to culture (Detects if a culture shakes hands, hugs...etc)	Eat noodles	Have biometric sensors within the arm to detect what other people think about you by using embedded sensors to
Warm or cold body while go outside in winter or summer	Cut steak automatically or in single hand	Detect how strong the user is shaking your hands.	

136

Appendix 2: List of Use Cases from Orochi's Focus Groups

Help feed me during lunch time, so I can work on other tasks	Help grasp objects for people who have a stroke or can't move their limbs	Give me more power to hold heavy objects	it can change its pose automatically based on the situation. When it is cold, it wraps around my neck to warm me, when it is hot, it wraps around like a belt
Hold a phone to show me anime while at home, following me wherever I go	When taken off at home and I'm browsing the internet, it can go autonomously to open the door for guests and greet them	While riding the bike to school, the robot can hold an umbrella for me	Reach high lofts at home that I cannot normally reach without standing on a chair
Cut and serve me food	use it like a servant or a pet, it can fetch or do things for me around the house (such as house chores…etc)	Help me hold heavy objects for longer periods of time	It could catch you if you fall or lose balance
Support weak/injured leg when walking up or down stairs	bring you a drink and feed you while relaxing at home	Help Disabled people like an exoskeleton for the legs or hands	Help you gain balance when you lose it by changing the pose and distributing its weight to stabilize you
Holding a book when reading in bed	Extend your reach, reach something away from you. Is something is far, it can wrap around your hand and extend to allow you to reach objects above the cupboard	Type on the pc using the tentacle	Turn off or on the stove while I cook, and my hands are occupied
turning notebook pages with small fingers	for walking, I would sit on this device, then this device would walk instead of me	Reach and access high objects around the house	Open/close fridge automatically when I get stuff from the fridge
Lift Heavy objects in the house, especially for weak people	it can be used like a chair when needed	Help me open the door when I can't use my hands	Cut fruits or vegetables quickly
Taking selfies using the phone	wear it like a helmet for protection while riding my bike	Hold my apartment door while I get a mail item from my delivery box	When eating outdoors, there is no table around to put food, so you can use it as a stand/extra hand to hold breakfast mug or plate
Rolling the wheels of a wheelchair	Can protect me when falling, transforming to a helmet if it is fast enough	Pick up things from the floor without me having to bend and pick them up	It detaches from you and gets me drinks from the fridge. For instance, when you are busy
Archaeological excavation on land and under water	use it to autonomously drive a car	Pick up and handle very tiny objects (needle, very small screws...etc)	Can help you press shortcuts, since your right hand is busy with the mouse and your left hand on the keyboard, it can help in pressing shortcuts without moving your hands
Holding smartphone for navigating after pointing the way	reaching object under the table or in narrow spaces	Hold on to many things at the same time, such as opening the door, holding my coffee or objects	Use it as an exoskeleton, where it can transform as a chair when I need to sit, or support my arm when I hold objects for a long time
Holding grocery bags while going home	Find and retrieve objects around the house. For example, if I lose my watch, it can go and find	Help me wear my shoes, take off my shoes without much effort from me to	it can help me run faster and turn better as it can balance me while

	it (Searching under the sofa, around the bed…etc) until it finds it	bend and take them/put them on	running at my maximum speed
Assist me in cooking (stirring food)	use it while farming; pick fruits that are too high or to do this task quickly	Pick up or retrieve objects from my bag, such as coins	Can help me dangle from a tree, or climb a tree using this strong robot
Cutting food when preparing ingredients to cook	use it like a stick to reach objects above a cupboard	Hold on the rails or inner wall of the subway to stabilize me	I want to use it to help me swim faster, it can act as a propulsion fan behind me by spinning the arms quickly
Use it as a chair	use it like a pet or companion at home	Can become a chair to wait in line at events or concerts	Use it to stabilize the camera when I take long exposure pictures
Assisted walking, reducing pressure on feet and legs, or use it as an extra leg	Fetch you objects, it can detach and go to retrieve objects for you	When the train suddenly stops, it can immediately stabilize me against specific objects or protect me from falling	Use it to hold the handle on a train so you can use your hands to use your phone
Pouring coffee for me while I work	use it to clean deep or narrow or unhygienic (toilet) locations in the house	Help me in the gym by holding weighs for me so they wouldn't fall on me	Use it as a stable and dynamic selfie stick
Holding my cup of coffee	Massaging my girlfriend or somebody while detached from me (not worn)	Act as my coach at the gym to help me exercise	Hold the phone for me so I can type with one hand on the touch screen quickly
Balance food or objects when being carried around	Use it as extra arms for massaging people or rehabilitation	Help me in climbing a mountain or building outdoors	Help me prepare coffee using the Moka pot, which is too hot, so it can handle the pot and put it on/take it away from the stove
Hold smartphone in the bathroom	bring you your wallet to swipe your PASMO (Train IC card) automatically	Help me climb and practice within indoor climbing areas (such as in amusement parks)	Help me prepare bread in a traditional oven, it is helpful to put things inside or take them outside since the ovens are too hot and deep
Opening the door automatically for me	Use it as an authentication device with built in NFC or other technologies	Help me detect dangerous situations, such as falling objects, where it can protect me	Play piano with an extra hand, which can enable me to compose new type of music
Playing games instead of me on a smartphone while I work.	can use it to push people away. People who might bump into you in crowded locations, like subway or in a festival	Help me take notes, it can hold a pen and write things instead of me	Use it to turn the pages while playing the piano
Holding umbrella while going to work	Use it to stabilize yourself in the subway by holding the handle or bars	Speech to text typing or writing, it can fill a form after we tell it what and where to write something	When I fix it to the bed rails, it can hold a book for me when I lay down and read. Even if I lay around, it can follow my head so I can read the book in any pose
Translating my speech to sign language	get something from the backpack	Hold a phone to take a selfie automatically	When the robot is detached from me, I would use it to hug my partner when we are away from each other
Stabilizing me in the subway when I am about to fall	Use it to tie my shoelace automatically	Get me a bottle of water when I am using the pc	While wearing the robot or when it is detached, I want to use it to hold my baby for me when I am busy doing some chores
Doing unhygienic work at home (e.g. handling and carrying trash)	Use it to wear glasses automatically when I need them, or take them off when I don't need them	While drawing on a pc, I want to use it as an input device to simultaneously control colors or other attributes while I draw	Swipe the oyster card (subway card) automatically upon approaching the tolling gates
Climbing on trees or mountain climbing	For mountain climbing, I can use more hands to	Flip pages while playing the piano	Hold the umbrella for me while I ride my bike

	hold the rocks, End-effectors can be used to have better attachment		
Cleaning and mopping surfaces at home	Eat chips without making your hand dirty	Maintain my pose when I sit and use the pc for a long time	I want it to fight robbers to protect me
Swing the tennis racket harder or move it faster	Feed you while working on the pc	Hold a baby while a mother is busy with other tasks	Use it to stretch my leg's muscles before training, It can wrap around my feet and stretch my legs just like trainers
Type on laptop with extra fingers	Use it to hold your camera, like a camera holder while skiing	Handle hot utensils while cooking, or while baking it can handle hot bread	When I am typing on a keyboard, it can help me move the mouse without moving my hands
Grabbing drinks and make me drink them hand free	scratch your back	It helps me cut hot meat/steak after I finish cooking them, it can cut more quickly and precisely	Hand me and make me drink the coffee so I wouldn't lose attention while typing on the keyboard
Eating chips hands free so it won't mess up my hands	when driving, it can get you objects from the backside autonomously without having to worry about controlling it.	For a waiter, he/she can hold many plates or cups and serve it to customers	Wrap it around the chair so I can use it as an armrest to support my hands when writing or typing on the keyboard
Holding datasheets, books or a tablet for checking data while typing on my pc	Self-defense when being robbed, it can defend you by pushing robbers away	Become like an exoskeleton to make me run faster	Use it to hand me objects automatically without me having to look for the object on the table. I can just say what I need and it hands it to me automatically
Calling someone with a phone	make you wear your socks or shoes automatically	use it as an exercise robot, similar to dumbbells for the hands. Because it has variable power, it can resemble different weights	Hand me objects that are beyond my reach within my workspace
Back support for posture correction when siting on a desk	use it as third leg in sports to run faster	It can act to as a whole gym, to resemble different exercises for your feet, hands, arms or back.	Hold PCBs for me when I assemble them
Do other tasks while typing (which is done with own hands), such as grabbing objects	use it as exoskeleton in the leg	help you eat or feed you when you are sick	Plug in a usb stick on the back of my computer
Automatically Turning lamps on/off when I am entering/exiting a room	use it as exoskeleton in the hands	wipe the windows clean in the house	Hold the smartphones, facing me, when I am developing mobile apps on different devices, so I can quickly see if an application works correctly or not
Pulling you toward/away different places in the office when seated on a wheeled chair	Use it to pick up the phone from the desk when you are busy working	help me lift paints or tools while fixing things at the house	Use it as an input device during lectures when I am writing notes on my notebook, I can use it instead of a mouse, especially when there is no space to put the mouse on the small student desks
Storing tools, such as colors for painting, with multiple pens/brushes/colors options	It can automatically get a pen and write something on a paper when you need to, you don't have to worry about taking important notes	Acting as a food waiter/server: bring and serve food for family dinners, so family members do not have to leave the table	Use the robot in the bathroom for self-hygiene
Working like Microsoft surface studio as input device, e.g. choosing colors by rotating manually the robot body or end-effectors	Use it to type on the keyboard, it can type quickly	help and save time by shaping pastry in different shapes before baking them	Use it to push the door and handle objects while in the toilet, so I wouldn't use my hands

Holding a phone so I can use it hands free	get objects far away on a large dinner table	Take out hot bread or food from oven	Use it to handle brushes or wash them with water while painting
Use it to scratch my back	hold objects so I can solder them or bolt them	Cook fried rice, since flipping the pan can be dangerous and requires a lot of skill	Goes around my back to automatically squeeze me and fix my back posture while being seated and working
Resting head on the robot when sleeping sitting	Use it as a spanner to tighten bolts	Bathe my cat, as one person I cannot hold my cat and bathe her, so it can help me bathe her and then dry her with a towel	Use it to hold the monitor, so it can actuate and move the monitor wherever I look or move around the work area
Use it to interact with my laptop (joystick, scroll wheel, mouse)	use it as a massage chair	assemble furniture automatically for me	Detach from me, then go fetch me a snack
Writing in a foreign language using a pen, e.g. writing Difficult Chinese characters	When I am tired, I can use it as back assistance when working	help me lift furniture components, or to assist me in assembling them	Feed me the snack and make sure I am well nutritioned while working
Holding a book while reading hands free	Help me maintain my posture while walking.	Do house cleaning work: mopping, swiping...etc	It can test my smartphone applications, I can deploy the apps on smartphones, then the robot can automatically be programmed to click on certain regions of the screen to test my apps
Performing semi-automatic operations, e.g. automatically stamping documents that you feed the robot	use it to control the mouse so I can focus on typing on the keyboard	Help me clean unreachable places (like high away or under the sofa)	Use it to make me coffee on the table, it can fetch a cup, pour hot water and put coffee then stir it
Wrapping around the leg, using one arm for two purposes, e.g. holding a book while typing on a keyboard	Use it as a mouse, I can twist it or use It to point at different areas of the screen	Retrieve objects where your hands cannot fit, like under the sofa	Use it as a neck rest while on the train or plane
It can be used to automatically type articles on the keyboard (using tentacle to type) and voice control to type things hand-free style.	Use it as input device for VR gaming	Hold the phone for me when I make a phone call, relieving my hands so I can do something else	Help me pull my suitcase around while commuting
Hold cigarettes if my hands are busy	if you drop something on the floor, it would go and get it immediately	Using the dial pad on a phone to call people when my hands are busy	Collision prevention system, it can redistribute its weight to make me go left or right to avoid colliding with objects or people when I am using my phone while walking
Make me smoke (hand me cigarette and make me smoke it)	Find small dropped things or lost things, because since it has sensors, it can find small or missing objects easily	Hold a cigarette for me when I smoke	In a crowded place, prevent others from colliding onto me by placing the hand around me and pushing them away
Light cigarettes/throw away after finishing	the robot can sense what you require and show you where the object or get the object for you	Hold a water bottle and make me drink when I am thirsty	Hold my coffee for me while walking, since it can stabilize the cup even if I stumble or run.
Reach inside the pockets, get something out (phone or cigarettes).	Answer the phone automatically when it rings while I am working	Use it to shoot videos outside similar to what youtubers do. It can be a smart selfie stick that moves around, follows you and knows the right angles to shoot from	Support my hand to hold objects while commuting, since I may become tired after some time
it can access front and back pocket to retrieve objects	Use it to move the mouse so I do not have to be near the desk	give or take objects and hand it to surrounding workers at the office,	Hold a book for me while I hold the rails while on a bus

		acting like an office mail man	
can put or grab things in the backpack	Holding multiple tools or objects for me while I assemble machines	When I arrive to work, it automatically opens the laptop and set up the work environment for me. The same thing when I leave	Use it for self-defense for women, to push away attackers
Hold a smartphone when walking around	Can hold an extra tool, so I can exchange it with the held tool by the robot to increase my efficiency	Push on/off buttons on my desktop below the desk. I usually have to bend and go under the desk to push those buttons	I want to use it to drive a car instead of me. It can steer the car to safety if the person passes out while driving or he/she is too sleepy
Securely hold my phone in public so it would not fall	Use it to hold multiple objects while walking so I would not lose balance	Connect cables or usb flash drives to a desktop below	As driving assistance. in dangerous situations while driving, it can automatically hit the brake pedals. It can react faster than my leg. Or it can help me by pushing the clutch automatically while changing gears in manual cars
I want to use it to cook something for me that I dont know how to cook	In a cold weather, when worn like a scarf, it can just go up and protect my face from the cold wind	help me press keyboard shortcuts, especially if I cannot memorize them (copy, paste, increase/decrease volume...etc) I only need to select then it would automatically know if I want to paste or copy...etc	Can hold a cigarette for you to smoke while you drive, so you would not be distracted while driving
Use it for posture support while sitting for a long time	Use it to hold a phone while walking	For teachers, it can help you write things on the board while teachers explain things or read from a book. It can help them hang posters or learning apparatus on the board while they are explaining things too	Help you play a new instrument that you dont know how to play
Support my hand for holding objects over long period of time	Hold and open an umbrella automatically when it rains	It can help me plug things on the power outlet below or behind the desk	You can play multiple instruments at the same time and become a one-man band
Grab or put things back to the backpack	holding light things (bottle, cup, phone or others)	Help me find objects on a messy desktop; I can tell it which objects and it would automatically tries to find it and hands it to me	I want to use it to play tennis, because it can swing faster. Or we can have a new form of tennis where each player has one extra robotic racket with much more power
Holding smartphone while walking	I want it to hold the phone in front of me while walking, so I can watch videos and listen to music without holding the phone	If my table is huge, it can retrieve objects that are beyond my reach	I want to use it for dancing, extra hands can be used to create new choreographies that include extra robotic limbs
cleaning surfaces and cooking instead of me	Use it as a selfie camera holder	If your boss is around and you are surfing the web, it can quickly switch the pages/applications to show them you are working	I want it to maintain my posture while walking
Support for reading books (flipping pages and holding a book for a long time)	autonomous driving for bicycles or old vehicles	It can automatically wrap and close your laptop in case of emergency so you can leave faster	I want it to carry the phone for me when I use the navigation application
Use the robot as a heavy object holder while putting the robot on the table, or	opening/closing doors	It can massage my back while I work at the desk	Hold a bottle of coffee/tea and make me drink it while walking. Usually, when I walk and

when putting the robot around me			try to drink, I spill the drink over me, but this robot may be able to stabilize my drink
support for injured - use it as prosthesis for my arm or leg when injured	Holding and adding salt to your cooking when needed	When I want to copy something from a book, it can hold the papers or the book instead of putting them on the table	Make a 3rd person video of myself while I walk in interesting locations. The robot can go around me to shoot 360 videos
Reach objects that are far away or heavy	Feeding you while you watch a movie/or while working	It can also flip pages automatically so I can type contents on the pc	Help me do the dishes quickly. I can hand it dishes; it would wash them then put them accordingly
Use it to touch things I don't want to touch with my hands (trash, toilet seat…etc	do trivial task, pushing waiter-call buttons or adding seasoning to food	It can automatically adjust light conditions in the room for me so I can focus on my work, For example, It can close or open the curtain or turn on/off lights.	Shake other people's hands when my hands are dirty or full
Shake many people's hands at the same time, such as during parties	Can become a pet snake to chat and play with	Help operate the printer or equipment autonomously. For example, If I want to photocopy, it can go, feed the papers to the photocopier, does the job and gets me the copies back.	I want to use it to drink juice or change the music while cooking, since my hands will be messy
Smartphone holder/charger that is always available	Use it to prevent others from bumping into me when it is very crowded (pushing people around and saying "excuse me")	Hold multiple objects while walking, such as a phone showing the map and an umbrella	It can crawl and alert others in case of a disaster like earthquakes
Use it as a selfie stick or to take selfies	use it as an extra leg to walk upstairs when the stairs are too long	Hold my umbrella and suitcases while walking	While travelling or outdoors, it can physically help me hold more objects, such as BBQ utensils or bags
Use it as an action camera holder	Help you open a bottle with one hand	Can hold the dog leash when outside walking the dog, so I can focus on other things	Use it as a chair when you are tired
Use it as a gimbal or stabilizer for camera or phone	Help me get or find things from my backpack. It can find little things and get them to me	Help me in various chores to take care of my pet	Use it as a chair while waiting for the bus

Appendix 3: Analysis of Exerted Forces

Objective: We carried out an evaluation of our robots to investigate the amount of exerted forces associated with each servo speed used within our first user study.

Procedure and apparatus: Similar to previous work (Jones et al. 2004), we evaluated HapticSnakes feedback capabilities by attaching a force sensor (UNIPULSE) as an end-effector, to both HS and HH, that is connected to a pc through a DC amplifier as shown in Figure 63. We analyzed HapticSnakes poses when delivering taps and concluded there were mainly two poses. The first pose is used to deliver feedback to inner regions (e.g. cells 2,3,10 or 11) and the second is used to deliver feedback to peripheral regions (e.g. 1,4,13 or 16). Therefore, we started with the first pose and tested feedback on cell 2, then tested the second robot pose on cell 13.
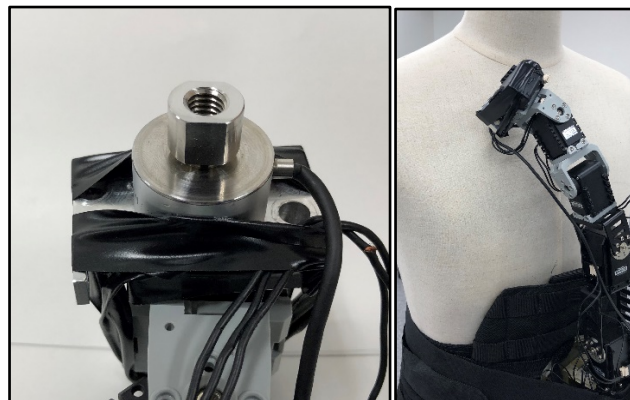
Figure 63 Left: we attached the force sensor as an end-effector for both HS and HH. Right: we tapped each location using the attached end-effector with varied speeds to measure the amount of applied forces in each robot at each servo speed.

We delivered taps to each cell to resemble weak taps with speeds of 5 rpm and 10 rpm, and strong taps with 20 rpm and 25 rpm as reported in user study 1. We repeated taps with each speed 10 times, therefore, we carried out a total 40 taps per cell (10 repetitions x 4 speeds). We followed this procedure for each the HS and the HH. All taps were conducted from a distance of 8 cm as specified in both user studies.

Cell Number	Servo Speed	Average Exerted Force
2	5 rpm	2.485 N
2	10 rpm	2.92 N
2	20 rpm	4.73 N
2	25 rpm	6.77 N
13	5 rpm	2.66 N
13	10 rpm	3.66 N
13	20 rpm	4.74 N
13	25 rpm	5.01 N

Table 5 Force evaluation of the HapticSerpent.

Cell Number	Servo Speed	Average Exerted Force
2	5 rpm	2.50 N
2	10 rpm	3.63 N
2	20 rpm	7.98 N
2	25 rpm	9.57 N
13	5 rpm	3.49 N
13	10 rpm	3.57 N
13	20 rpm	4.62 N
13	25 rpm	7.32 N

Table 6 Force evaluation of the HapticHydra. When compared to the HapticSerpent, the HapticHydra heavier weight enables it to exert slightly stronger forces at higher speeds.

Results: The results show a correlation between the speed and amount of exerted force. HapticHydra is much heavier and equipped with stronger motors, therefore, it is able to exert stronger forces when tapping because of its weight. As weak and strong taps were calibrated subjectively, we believe the amount of exerted forces by HapticSnakes lies within the reported ranges and servo-speed and cell type

Appendix 4: Males and Females Accuracy Analysis

This section contains 2 figures that illustrate the differences between the accuracies of males and females in all conditions of our user study.

Figure 64 this figure shows the distributions of the accuracies comparing male and female participants using HH on the back torso.
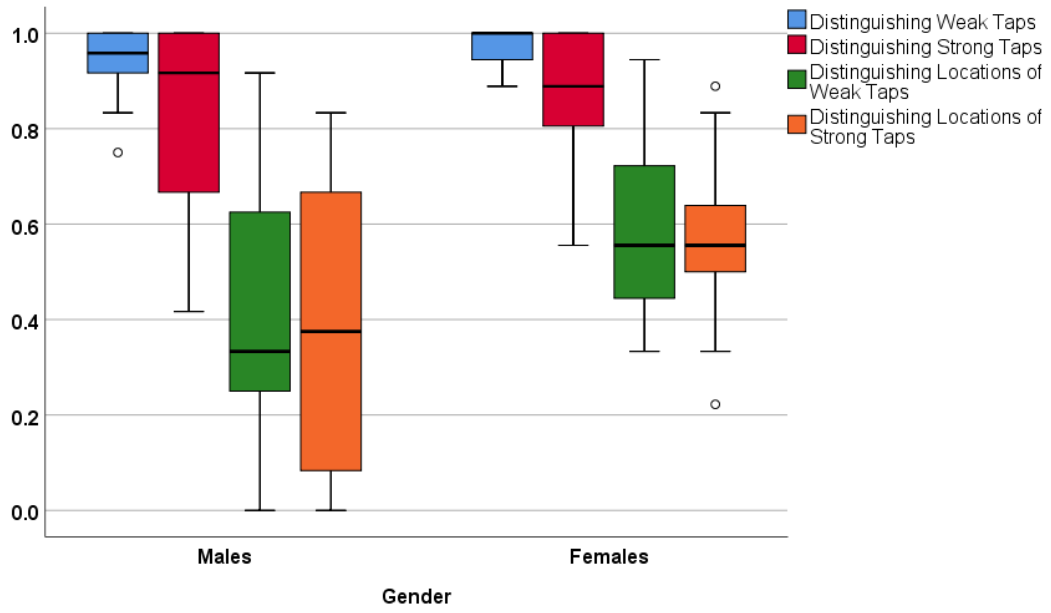
Figure 65 this figure shows the distributions of the accuracies comparing male and female participants using HS on the front torso

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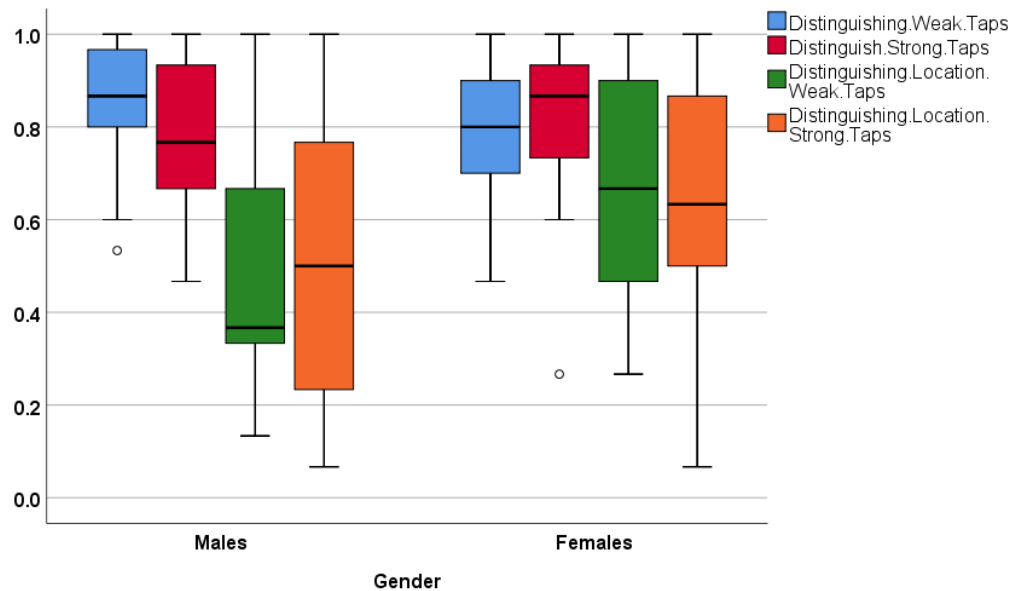Al-Sada, M., T. Hoglund, M. Khamis, J. Urbani and T. Nakajima (2019). Orochi: Investigating Requirements and Expectations for Multipurpose Daily Used Supernumerary Robotic Limbs. Proceedings of the 10th Augmented Human International Conference 2019. Reims, France, ACM: 1-9.

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A Perspective of Embodiment Informatics

Many people argue that the main goal of science is to serve and improve human life. Scientists around the world diligently conduct research in an attempt to uncover new knowledge, figure out patterns or establish technologies that can solve problems or offer a better life. Regardless of the huge amounts of accumulated scientific knowledge in our modern age, a huge amount of knowledge remains confined to scientific papers, failing to materialize and contribute to improving our lives. Such failures should drive us to think of why such discoveries have failed to materialize? and why have we invested so much time to uncover knowledge that finally ended up being overlooked or trapped in research literature? In this chapter, I intend to convey my understanding of Embodiment Informatics, and how the significance of such concept contributes to society and the world.

My understanding of Embodiment Informatics consists of three essential aspects. First, the strong multidisciplinary scientific investigation and evaluation approaches that enable eliciting knowledge from multiple scientific disciplines. The second is a materialization approach that allows transforming cross disciplinary knowledge to tangibles. Third, sustainability of tangibles, by attaining the ability to positively contribute to humanity through products, services or practical knowledge. My vision of embodiment informatics encompasses a number of challenges, which are briefly discussed. In addition, I will present how my proposed perspective builds upon the inventor's mindset that has existed throughout history. Finally, I will wrap up with conclusion of my perspective and related challenges.

A Strong Scientific Sense for Cross-Disciplinary Knowledge

Humans never stopped thinking about the universe and the world, fostering new ways to better ourselves, our environments or our lifestyles. In the last century, we have witnessed a lot of great discoveries, ranging from space exploration, to genome identification among other scientific breakthroughs. Nevertheless, I believe that many scientific breakthroughs failed to materialize due to the lack of the embodiment mentality; which is the inability for a researcher, company or institute to bridge the gap between knowledge and realization. Such mentality requires a thorough set of skills, abilities, training and a mindset that can understand how to conform scientific knowledge onto tangible.

174

In my opinion, the first and most critical aspect of embodiment is a strong scientific sense, which corresponds to robust research skills that enable conducting work with utmost scientific standards. Such abilities require numerous sub-skills, such as thorough investigation abilities, data elicitation, and analysis among others. A researcher should first be able to recognize relevant advances in specific scientific fields that are relevant to intended realization. This recognition provides an accurate starting point of where a scientific investigation should be heading. Second, investigation skills allow modelling effective investigation approaches that allows building upon recognized knowledge. Third, data gathering, and analysis skills enable developing, selecting and employing suitable scientific research methods and evaluation methods. Overall, I believe mentioned mindset and skillsets are the cornerstone of embodiment.

Realizing a service or a product has an extremely multidisciplinary nature, requiring a strong scientific sense, industrial and prototyping skills, as well as a good business mentality. For instance, successful realization of an electronic product requires good knowledge in electrical engineering, electronics engineering, human factors and ergonomics among many other fields to realize design concepts in a product. In addition, to effectively make a difference in people's lives, such product requires marketing strategies, business planning, product management skills and cross-cultural attitudes in order deliver such product to worldwide markets. Therefore, concept realization demands cross-disciplined and cross-cultural knowledge.

Multidisciplinary scientific knowledge is crucial in successful embodiment. By nature, realization of a concept demands integrating knowledge from diverse fields, fusing years of findings and breakthrough into an object or a service that makes a difference in the world. Therefore, although it is essential to attain multidisciplinary knowledge, there are a number of factors that may reveal numerous tradeoffs when emphasizing cross-disciplinary research. For instance, *which scientific disciplines and fields are deemed suitable to learn about?* It is a difficult question to answer, as it largely depends on the underlying immediate and long-term goals as well as future work direction. Moreover, with many scientific societies, conferences and journals, with large overlapping disciplines, and often contradictive findings, it is also difficult to determine which society is correct. Another question is *how multidisciplinary knowledge should be?* Knowledge within fundamental disciplines, such as physics or mathematics, have existed and matured for hundreds of years. Mastery of one scientific field is crucial towards the success, yet knowledge in one domain is not enough for embodiment. Likewise, spreading too thin across multiple disciplines does not enable the beholder to foster any success in all disciplines. Establishing the base line of which knowledge is needed across various disciplines, as well as expertise in specific disciplines is very challenging.

Concept-Materialization Mindset

Additional skills to materialize concepts into tangibles are essential towards the approach of embodiment. I believe that hands on skills in design, human factors, prototyping and manufacturing are critical in an embodiment approach. Hands on skills enable forging tangibles, whether as devices or systems, easily and rapidly. The faster a concept is transformed to a tangible, the more evident its' faults and advantages become. Therefore, rapid prototyping approaches have become common due to their robustness in mentioned aspects. Human factors and ergonomics play a major part of recent advancement in modern technologies, especially when developing systems or devices for users. Various success stories, such as with Apple or Microsoft, are essentially attributed to refinement and implementation of breakthroughs of such disciplines by shaping and integrating them into products and services. Although the original scientific findings and knowledge have existed for a long time within academic communities, the importance and impact of such findings has not

been evident until recent times; when such findings materialized and made a critical difference in our usage of devices and systems.

Sustainability of Innovation

I believe that a critical aspect of embodiment is the ability to shape tangibles as a product or services that ensures their sustainability in contributing to improving our lives. Accordingly, entrepreneurship, managerial and marketing skills are among the most essential skills in materializing ideas into sustainable products. Such transformation demands careful delegation among monetization and sustainability-planning aspects, which ensure deliverability and continuity of innovation. These factors additionally backtrack towards manufacturing and prototyping methods, especially as production scalability and sale feasibility depends on managerial and funding aspects that generally dictate the development and lifespan of a product. In order to steer the process of innovation, robust managerial and analysis skills, such as project management, planning, resource allocation, are critically required to ensure deliverability during the concept-to-tangibles transformation process. Finally, marketing and presentation skills ensure market adoption and proper presentation of proposed concepts, which lead to success and profitability, and thereby sustainability. In conclusion, the ability to successfully convert innovative concepts into a tangible object require a wide spectrum of business-oriented skills that both increase the probability of scalable materialization, maintainability of product lifecycle. I believe such abilities are essential to ensure the sustainability of tangibles.

In continuation to the above aspect, *soft skills* consist of a huge part of highly critical assets that support the realization process. Soft skills cover emotional intelligence that determines different attributes in relationships among people. Nowadays, success stories are mostly formed by groups of people that cohesively move towards a target under one leadership. Numerous literature and training courses emphasis the importance of such skills, which are not easily attainable, especially leadership skills. Moreover, these skills govern success in multiple internal and external scales. For instance, internal relationships between individual team members, team-to-team and on a larger scale of multidisciplinary groups consisting of multiple sub teams, are essential towards fulfilling the mentioned cycle of realization. Externally, the ability to liaise with outer entities, that are part of supply chain, product manufacturing or other business processes, is a crucial aspect of today's industrial and business environment. Therefore, the ability to understand such relationships, inspire and motivate teams and lead them towards realization targets collectively affects the capability of embodying innovation. Soft skills do not diminish any of the previously mentioned personal attributes or skill sets, but rather builds upon such characteristics and extends those outwards and towards interpersonal relationships, especially since such relationships continue to rise in importance in both industrial and academic fields. In addition, such skills are very delicate in the sense that they are affected by multiple factors, such as by culture, environment or personality. Therefore, person must be aware of such characteristics to cope accordingly with every unique relationship.

Embodiment Informatics

My perspective of embodiment informatics comprises the combination of strong scientific sense in distilling cross-disciplinary knowledge, and a strong concept-materialization mindset and skillsets. In my humble opinion, I believe that embodiment as a whole is closely related to the inventors' mindset that has existed throughout history. Such mentality is not a new form of thinking, but rather a reformation of the scientific approach within applied science and engineering as a whole. I believe that many inventors, such as Sakichi Toyoda and Thomas Edison, could embody advances in various scientific disciplines as tangibles that made a difference in our lives. Such materialized inventions did not remain behind closed lab doors

or hidden in closets, but rather extended beyond. We can clearly see the three aspects of mentioned perspective within the outcomes of mentioned inventors: *strong scientific sense, the ability to develop tangibles and finally to sustain such outcomes and make differences in people's lives.* For instance, there have been several trials to invent a working electric light, but previous trials have failed due to commercial impracticality, an aspect that Thomas Edison has proved to be superior at through his ability to experiment with multiple materials until he succeeded. Later, Edison could sustain such product through entrepreneurship, by commercializing his product, not just in the USA, but also beyond, thereby positively impacting humanity. Such ability to fuse sciences into materialization is very noticeable in many success stories, yet, I believe such success was largely accomplished because the individual's mentality and skillsets that resemble the embodiment informatics perspective. Nevertheless, my vision of embodiment informatics differs in the fact that it formalizes the same process into a framework of approaches, methods and skills that can be systematically attained and used

Even though my vision and perspective of Embodiment Informatics consist of multiple aspects that cover a wide spectrum of approaches, I believe that such vision has important challenges. The first challenge lays in the suitable balance in gaining all mentioned approaches and skillsets. Although multidisciplinary knowledge proves to be beneficial in having a birds-eye view, the inability to gain sufficient knowledge and continuous expertise in one discipline poses a threat to success. An important question I raise *is how multidisciplinary the required knowledge should be?* I believe the answer is largely subjective, as it is strictly dependent on the intended outcomes. The target of my vision must clearly be identified prior to implementation, as related scientific backgrounds and skill sets are largely relative to the work domain. In addition, there is a challenge in balancing soft skills with scientific backgrounds. Most leaders, such as company CEOs, do not poses strong hands-on knowledge or expertise in latest technologies, but rather, have the leadership mindset, powerful soft skills and the strong fundamental scientific backgrounds. These skills in turn enable CEOs to deeply realize the direction of current technologies and guide their companies towards success. Thus, balancing managerial aspects, soft skills with other personal traits is essential, as this balance determines whether we have strong scientific researchers that lead scientific breakthroughs, or future industry leaders that can guide individuals to business success.

In conclusion, my perspective in embodiment informatics consists of three essential aspects. First, it includes the scientific foundations that consist of investigation and evaluation skills that enable probing relevant scientific disciplines to culminate knowledge. Second, the ability to realize scientific knowledge through business-oriented mindset that encourages concept realization. Third, the ability to deliver tangible and sustain outcomes to positively contribute to humanity. There exist a number of dilemmas that require careful and delicate balance, such as in determining suitable backgrounds and deciding how multidisciplinary such scientific foundation should be. Finally, I emphasized that the proposed concept of embodiment informatics is not totally new, as it builds upon previous mindsets and methods witnessed with notable inventors. However, such inventors resorted to developing the three essential aspects of embodiment informatics by themselves, enriching their own skillsets and approaches to achieve sustainability of their outcomes. My proposed concept of embodiment informatics builds upon mentioned facts by envisioning a framework that builds upon novel mindset with suitable methods and approaches that match modern research and business challenges. Therefore, I think embodiment informatics is essential for positively contributing to humanity, as it bridges the gap between scientific advancements, realization and sustainability, allowing scientific knowledge to have a positive touch in our day-to-day lives.

Research Achievements

◯ indicates substantial contributions to this dissertation

Journal papers	◯ M Al Sada, K. Jiang, S. Ranade, M. Kalkattawi & T. Nakajima, (2019). HapticSnakes: multi-haptic feedback wearable robots for immersive virtual reality. Virtual Reality, 1‑19 (to Appear) DOI: https://doi.org/10.1007/s10055-019-00404-x
Conference Proceedings	◯ <u>Mohammed Al-Sada</u>, Thomas Höglund, Mohamed Khamis, Jaryd Urbani, and Tatsuo Nakajima. 2019. Orochi: Investigating Requirements and Expectations for Multipurpose Daily Used Supernumerary Robotic Limbs. In Proceedings of the 10th Augmented Human International Conference 2019 (AH2019). ACM, New York, NY, USA, Article 37, 9 pages. DOI:https://doi.org/10.1145/3311823.3311850 ◯ <u>Mohammed Al-Sada</u>, Keren Jiang, Shubhankar Ranade, Xinlei Piao, Thomas Höglund, and Tatsuo Nakajima. 2018. HapticSerpent: A Wearable Haptic Feedback Robot for VR. In Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems (CHI EA '18). ACM, New York, NY, USA, Paper LBW624, 6 pages. DOI:https://doi.org/10.1145/3170427.3188518 ◯ J. Urbani, <u>M. Al-Sada</u>, T. Nakajima and T. Höglund, "Exploring Augmented Reality Interaction for Everyday Multipurpose Wearable Robots," 2018 IEEE 24th International Conference on Embedded and Real-Time Computing Systems and Applications (RTCSA), Hakodate, 2018, pp. 209-216. DOI: 10.1109/RTCSA.2018.00033 ◯ <u>Mohammed Al Sada</u>, Mohamed Khamis, Akira Kato, Shigeki Sugano, Tatsuo Nakajima, Florian Alt. Challenges and Opportunities of Supernumerary Robotic Limbs, In Amplify '17: Proc. of CHI 2017 Workshop on Amplification and Augmentation of Human Perception. May 6 - 11, 2017. ACM, New York, USA. ◯ Jiang K., Piao X., <u>Al-Sada M.</u>, Höglund T., Ranade S., Nakajima T. (2019) A Robotic Haptic Feedback Device for Immersive Virtual Reality Applications. In Ambient Intelligence – Software and Applications –, 9th International Symposium on Ambient Intelligence. ISAmI2018 2018. Advances in Intelligent Systems and Computing, vol 806. Springer, Cham DOI:https://doi.org/10.1007/978-3-030-01746-0_17

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