Orochi: Investigating Requirements and Expectations for Multipurpose Daily Used Supernumerary Robotic Limbs

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ABSTRACT

Supernumerary robotic limbs (SRLs) present many opportunities for daily use. However, their obtrusiveness and limitations in interaction genericity hinder their daily use. To address challenges of daily use, we extracted three design considerations from previous literature and embodied them in a wearable we call Orochi. The considerations include the following: 1) multipurpose use, 2) wearability by context, and 3) unobtrusiveness in public. We implemented Orochi as a snake-shaped robot with 25 DoFs and two end effectors, and demonstrated several novel interactions enabled by its limber design. Using Orochi, we conducted hands-on focus groups to explore how multipurpose SRLs are used daily and we conducted a survey to explore how they are perceived when used in public. Participants approved Orochi's design and proposed different use cases and postures in which it could be worn. Orochi's unobtrusive design was generally well received, yet novel interactions raise several challenges for social acceptance. We discuss the significance of our results by highlighting future research opportunities based on the design, implementation, and evaluation of Orochi.

CCS CONCEPTS

• Human-centered computing~Human computer interaction (HCI)

KEYWORDS

Design; Augmentation; Wearable; Multipurpose; Unobtrusive;

1. Introduction

The diversity of daily interactions presents numerous interwoven challenges that a single-purpose wearable cannot address. Therefore, a fundamental aspect of the vision of wearable computers is being generic; they can adapt their interaction modalities to conform to the diversity of interaction contexts [32]. A single-purpose wearable can be efficient within a specific domain, but daily worn devices require genericity to be applicable in a variety of contexts. Recent research also affirms the need for genericity, as users prefer multipurpose wearables over single purpose ones for daily use [19].

Wearable robots present numerous interaction potentials. Supernumerary Robotic Limbs (SRLs) [23] are wearable robots that augment humans with additional physical manipulation capabilities. Research in this emerging domain has presented SRL prototypes that demonstrate their potential for daily use. However, incorporation of SRLs into daily life faces the same challenges that impede the realization of mainstream general-purpose wearables. An SRL worn daily should include multiple interaction capabilities to increase its value for use. To the best of our knowledge, no previous work has investigated multipurpose SRLs that both address challenges in wearability and everyday use.

Figure 1 Orochi is a multipurpose SRL that a) can be worn and used across daily contexts and b) is unobtrusive in public.

We first extracted three design considerations that address the mentioned limitations of SRLs, emphasizing interaction

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genericity and unobtrusiveness during daily use. To demonstrate our concepts, we embodied these considerations in a wearable robot that we call Orochi (Figure 1). The considerations are: *1) Multipurpose use:* we demonstrate through multiple novel applications that Orochi expands the usage scope of previous SRLs, which mainly focused on industrial applications [5,6,23] or physical manipulation [31,34], to include scenarios in daily life, and haptic and shape-changing experiences. *2) Wearability by context:* Orochi is easy to wear and can be worn differently by context. In contrast, current SRLs are relatively heavy, difficult to wear [5,6,34,35], and are fixed to a specific location on the body [31,34]. *3) Unobtrusiveness in public:* Most surveyed SRLs (e.g. [5,31,34]) are bulky and unable to retract when not in use, making them obtrusive and noticeable. Orochi remains inconspicuous in public as it retracts and blends in with clothes like a garment.

Our implementation comprises a serpentine (snake-like) robot with 25 degrees of freedom (DoF) and two end effector types (Figure 1). Although Orochi is not the first serpentine robot, Orochi is the first multipurpose SRL to utilize a snake form factor for assistance in activities of daily life. We explored how a number of novel interaction opportunities are enabled through the design considerations in Orochi, such as simultaneous interaction with objects in front of and behind users.

The second part of our work addresses the scarcity of works about usage expectations and challenges of realizing daily used multipurpose SRLs. Therefore, we evaluated Orochi based on two unexplored domains: *1) How can a multipurpose SRL be used within daily contexts? 2) How is a daily worn SRL perceived when used publicly?* To achieve our first objective, we conducted four hands-on focus groups. Participants confirmed Orochi's multipurposeness by proposing a variety of real-life use cases, which we analyzed and we highlighted different usage categories within daily contexts. Participants also wore Orochi differently by context, addressing our second design consideration.

For our second evaluation, 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.

Our contribution is two-fold: 1) The extraction and development of three design considerations for multipurpose SRLs from related literature and their embodiment in Orochi. 2) The evaluation of Orochi's compliance with the design considerations through a series of focus groups and a user survey.

2. Background and Related Works

Our work mainly builds on three strands of previous works; SRLs, multipurpose SRLs and shape-changing interfaces. We describe how our work extends these domains as follows:

2.1. 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 or drilling holes [5,6]. Other works, such as [35], focused on generic grasping and manipulation of physical objects without emphasizing professional work contexts.

Within the context of professional work, a significant portion of related work focused on supernumerary robotic (SR) arms, which are typically mounted on the user's back [5,6,31] or upper arms [34]. Other works presented SR fingers, which attach to the user's wrist to augment the hand with capabilities, such as holding large or multiple objects in a single hand [35].

Compared with previous research, Orochi's novelty lies in its multipurpose nature, which makes it applicable to a larger domain of tasks than previously investigated. It comprises both a long SR finger and an arm that can flexibly be extended from different parts of the body, thus providing unique interaction opportunities.

2.2. Multipurpose SRLs

An emerging sub-category of SRLs attempts to enable multipurpose use through flexible designs. Work in this domain is very scarce, but Leigh and Maes published a notable piece of related work on robotic symbionts [20], 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 also presented a reconfigurable SR finger that enabled a variety of interactions through a modular design [21].

Orochi embodies the three design considerations, and therefore, tackles challenges of daily use that have not been previously emphasized in surveyed works. For example, Orochi's design makes it applicable to a larger domain of tasks than have been previously investigated. Orochi also advances the state of the art through its limber structure, which allows it to be worn in multiple ways and remain inconspicuous in public.

2.3. Shape-Changing Interfaces

Shape-changing interfaces use alterations of physical properties to create various interactive modalities [29]. LineFORM [25] 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 [26] presents a similar concept, which includes input and output methods, along with a user-modifiable robot morphology, which further expand its possible applications.

While Orochi shares 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 [29]. 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 [29]. In contrast, multipurpose SRLs essentially augment users' physical interactions with their surroundings, while offering digital interaction possibilities. The challenges of multipurpose SRLs [20,21], like Orochi, include control, automation, user-robot task coordination methods, and capable actuation methods to lift or manipulate objects [17]. Such challenges are not as essential for shape-changing interfaces.

3. Design of Orochi

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 wearables. These considerations are essential for designing multipurpose daily used SRLs and therefore form unique requirements that have not been fulfilled in SRL works.

3.1. Multipurpose Use

Previous approaches emphasized the need for multipurpose daily wearables. For example, Clawson et al. [8] and Lazar et al. [19] suggested that having several wearables for different uses is not desirable, underlining the need for multipurpose wearables. Al Sada et al. [2] found that potential users of SRLs regard multipurpose use as a main requirement. However, few works have investigated multipurpose SRLs [20,21]. We classify daily interactions and focus on the following domains:

(A) Interaction with Physical Surroundings: SRLs may provide different types of physical interaction capabilities. 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 [35], beyond arm's reach, or dangerous to handle, such as chemicals [34].

(B) Digital Interactions: Along with physical interaction with the real world, wearable robots can feature a myriad of sensors and mechanical components that can be used with digital services [8,20,27,28]. Based on surveyed works, we highlight the following experiences that are promising for multipurpose SRLs.

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 has demonstrated applications, such as a haptic input device [20] and haptic feedback to various body parts [3].

Shape-changing experiences: Physical morphing of the wearable can be utilized to convey information, for example, to present an icon resembling a specific state or condition [25,28].

3.2. Wearability by Context

Gemperle et al. [14] define wearability as the active relationship between the wearable's physical shape and the wearer's body. This concept includes many factors, such as a device's weight, shape, and ergonomics [10,14]. However, within the scope of our work, this design consideration comprises two main aspects. First, the ability of a wearable to be worn in various locations and in various ways as needed. 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 second aspect is the ability to quickly wear or take off the device. In addition to being a wearable, the robot may serve more purposes when detached, such as interacting with objects at a distance from the user [20], or functioning as an external input device [25].

All surveyed SRLs rely on strapping mechanisms for attachment to the user's body [5,6,34,35], which have disadvantages. First, they constrain the robot to one location on the body, therefore limiting the workspace to that location. They are also cumbersome to wear, especially with larger robots, and the user may require assistance in attaching them [5,6,23].

3.3. Unobtrusiveness in Public

Fashion wearables [24,27] couples aesthetic and functional aspects. This combination not only aesthetically enhances the wearable, but also decreases the social pressure associated with public use of devices of novel form factor [24,27,33]. However, previous SRL prototypes are quite obtrusive, especially as most of them are bulky or aesthetically abnormal. We therefore set the following requirements to address these challenges:

(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 [27]. Aesthetic considerations of a wearable also contribute to its unobtrusiveness. For example, several investigated prototypes in related work were shaped as everyday garments, such as a belt [9] or a scarf [28]. These 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 shaped as an arm, such as [31] and [34], is unable to retract due to its fixed location and rigid mechanical design. Such a design leaves the robot protruding from the body even while inactive, which poses potential hazards such as collisions with the surroundings.

4. Realization of Orochi

4.1. Embodying Design Considerations in Orochi

Snake robots have long been investigated within robotics communities [16]. The flexible structures of snake robots allows them to be versatile across a wide range of tasks, such as search and rescue [11], inspection [15], or manipulating objects [17]. Therefore, we implemented Orochi as a serpentine robot with 25

DoFs and two end-effector types. While Orochi is not the first serpentine robot, it is the first to use the snake formfactor 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:

4.1.1 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 2 a, and d). Orochi's end effectors can be used as always available haptic interfaces with devices like head-mounted displays. The flexibility brought by many DoFs also allows Orochi to take various shapes for conveying information (Figure 2 c).

4.1.2 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 3). 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.

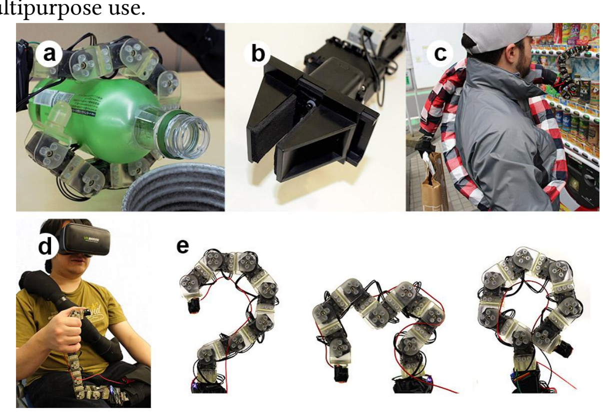

Figure 2 a,b) Orochi is equipped with two different end effectors, c) where they can be used to augment user's interactions in different ways. (d) Its end-effector can be used as a haptic input method, such as for VR, e) or take different shapes, such as "?", "M", or "Q" to convey information.

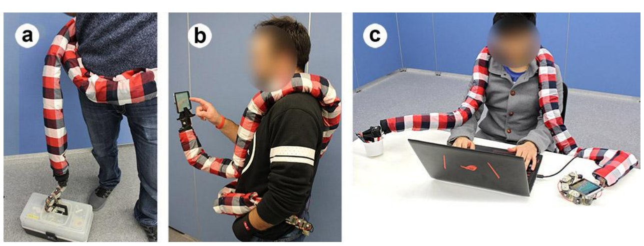

Figure 3 Orochi can be worn differently by context, such as a) around the waist to access objects below, b) above shoulders to hold a smartphone, or c) around shoulders to manipulate surrounding objects.

4.1.3 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 4), 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 4 b,c,d).

4.2. The Implementation of Orochi

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

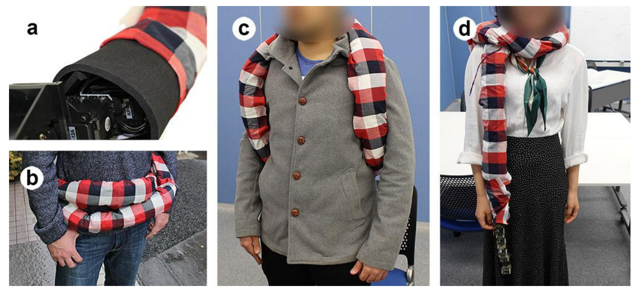

Figure 4 a) Orochi is covered by two layers, contributing to comfort and improved aesthetics. b,c,d) Orochi's can be worn in different ways, resembling common garments.

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.

4.2.1 Robot Structure

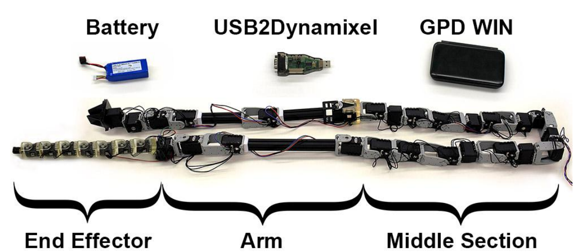

Figure 5 Orochi's hardware components. Its length can be adjusted by adding or removing servos in the middle section.

Orochi consists of a chain of Robotis Dynamixel servomotors [38] (Figure 5). Its 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 DoFs, a thickness of 42mm (with cover), and a weight of 1.4 kg in a configuration that is easily wrapped around the user's body in multiple ways. Orochi's structure includes the following sections:

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

Arm sections: Both arms have four AX-12A servomotors, and the right arm includes a stronger MX-64AT servomotor connecting it to the middle section for better handling of 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, instead of using longer chain of servomotors.

End effectors: End effectors can be attached to both arms, and Orochi was tested with two types of these. A parallel gripper, using an AX-12A servomotor, was installed at the end of the stronger, right arm of the robot (Figure 5), 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 DoFs of the tentacle enables flexible wrapping and delicate manipulation of objects. For example, it can press buttons, grasp bottles, and perform other highly dexterous tasks.

4.2.2 Actuation, Mechanical Design and Power

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. We chose these motors because of ease of mechanical connection in different configurations and the available software libraries for control. Previous approaches, such as [6,23], 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. While our actuation design is similar to those of [20,25,26], our design differs as we distributed 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.

Orochi is powered by an 11.1 V, 3500 mAh, lithium polymer battery, which can power the robot for approximately 20 minutes of use. An external power supply can be used to power Orochi.

4.2.3 Control

Deployed on a small computer [39] (Figure 5), our toolkit was developed to rapidly experiment with different configurations and morphologies. First, we abstracted the Robotis SDK so its functions are easily invokable from higher level modules. Next, we developed a network interface using WebSockets, that allows us to invoke robot functionalities. This network interface facilitates experimenting with different control, motion planning systems, and input or output devices.

We developed a graphical user interface that provides easy access to all our robot controls. It also includes a movement generator and player system that allows users to create, save, and play back movements and sequences. To create a movement, the user physically moves the joints to the desired location and saves it as a motion. Sequences can be created by combining movements and can then be played back with varied attributes (e.g. speeds). Both movements and sequences are network-invokable. This was done for prototyping purposes, as building a completely autonomous robot is out of the scope of this work. Yet, the current software can be extended for higher autonomy by integrating intelligent motion planning systems or sensors.

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 3 a, Figure 6 a). Orochi can also extend the reach of the user's arm, enabling them to interact with objects at a distance (Figure 6 b). 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 6 c, d).

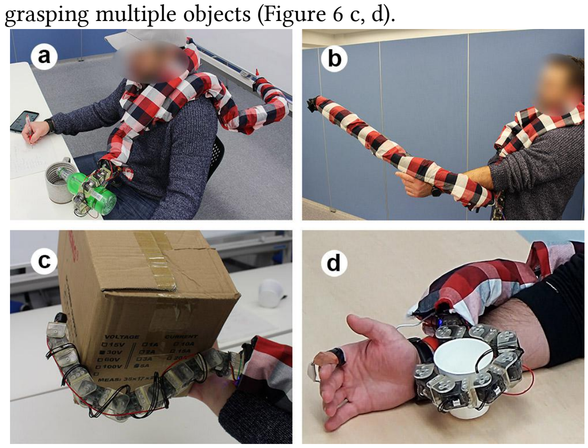

Figure 6 Orochi can seamlessly augment the user with a) an extra arm in front of or behind the user, b) extend hands reach, or augment them with extra fingers to c) grasp large objects or d) to hold more objects.

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 [3]. These include, for example, tapping, gestures, pinching, or pulling users' clothes (Figure 7 a,b) .

Figure 7 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 7 c), 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 7 d).

6. Evaluation

6.1. 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 [7,30].

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.

6.2. Unobtrusiveness Survey

Although Orochi was designed to be publicly unobtrusive, how users wear or use Orochi may draw different levels of undesired attention [9]. Surveys have been shown to be effective for studying social acceptance of emerging systems [7], therefore, we designed a survey to investigate how noticeable Orochi would be when worn in public. We hired 40 participants, coming from 15 countries, varied backgrounds, aged between 19-67 (*m*=28.12, 8 females). The survey depicts participants as spectators [7]; 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 9, 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.

7. Results and Analysis

7.1. Focus Group Results - Use Case Analysis

Similarly to previous work [2], we extended the categories in activities of daily living [18] 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 diversity of collected use cases indicate that participants perceived Orochi as a multipurpose SRL, therefore satisfying *multipurpose use*. One participant said, "*I like the* *possibility of doing anything I want with it.*". We believe that the results have expanded our understanding of users' interaction expectations within daily use. We discuss the results implications, opportunities, and challenges within the next section.

7.2. Focus Group Results - 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 8). Yet, as our current SRL 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 contexts.

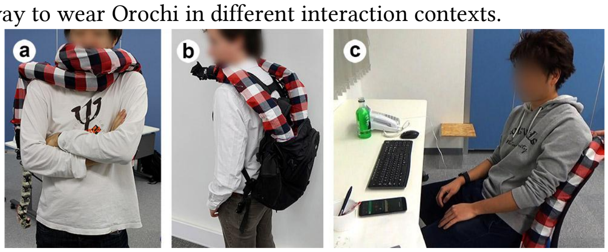

Figure 8 a) One participant preferred wearing Orochi as a scarf that automatically covers his face when it is cold. b) One participant placed it in a backpack, and another c) around his seat, doubling as back support and to retrieve objects.

7.3. 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."*. Nevertheless, survey results reveal further insights. 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 9), and 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.-

	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 9 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).

8. Discussion and Future Work

8.1. Embodying the Design Considerations

Our presented design considerations are generalizable and can be realized differently. We believe the key to multipurpose use is adaptability in the wearable's structure to conform to different contexts. Therefore, research on reconfigurable robots [37] and shape-shifting robots (e.g. snake robots [15,16]) is essential. 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. Orochi 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, a modular SRL body or end effectors, and investigating new robot morphologies.

Wearability by context and unobtrusiveness are substantial for increasing Orochi's uses and enabling daily wearability across numerous contexts. Future work should explore additional means to realize these two considerations. For example, an SRL may be designed as a crossbody 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, we believe the research on reconfigurable and shape-shifting robots should be a starting point to explore future multipurpose SRL formfactors, while our design considerations form a baseline for directing future work towards fulfilling requirements and expectations of daily worn SRLs.

The use case analysis is a valuable resource for designing, refining and gauging future SRLs against realistic usage expectations and requirements [4]. Functional requirements can be created based on our gathered tasks to ensure suitability of SRL 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 SRL designs. Therefore, we make all the use cases accessible [40].

8.2. Research Opportunities and Challenges

We discuss major design implications, opportunities and challenges that arise from the design and evaluation of Orochi.

Designing SRLs 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* [1]: Orochi is generally perceived as a tool for extending users' physical interaction capabilities [20], 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* [1]: 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, 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 [12,22], for example, using EMG-synergetic controls [20,35] or passing control to the user's limbs (e.g. leg [31]). As a companion or embodied agent, implicit interactions with higher autonomy [12] and anthropomorphic interactions [13] 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 SRLs replace smart devices or will SRLs interact with them? SRLs 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 7 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 [36], future research should analyze and identify potential risks and investigate safety mechanisms that are suitable for daily used SRLs.

9. Conclusion

This paper presents Orochi, a multipurpose daily worn SRL designed based on three design considerations: multipurpose use, wearability by context, and unobtrusiveness in public. We provided our vision of how these factors could be embodied. We validated Orochi through four focus groups and a survey. The use case analysis served as a first step to explore potential usage domains for this emerging type of wearables, while survey results revealed social acceptance challenges in daily use. We highlight research challenges and future research directions to advance this domain. While some challenges intersect with existing research domains, the majority are unique and have yet to be explored. Overall, we believe multipurpose SRLs will play a larger role in future daily interactions, where they would become part of daily attire and augment our interaction with digital and physical worlds.

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