Figure 1: Sample sketches by participants demonstrating use cases for Supernumerary Robotic Limbs (SRLs).

Challenges and Opportunities of Supernumerary Robotic Limbs

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Abstract
Recent advancements in robotics and wearables made it possible to augment humans with additional robotic limbs (e.g., extra pair of arms). However, these advances have been dispersed among different research communities with very little attention to the user's perspective. In this work we take a first step to close this gap. We report on the results of two focus groups that uncovered expectations and concerns of potential users of Supernumerary Robotic Limbs (SRLs). There is a wide range of applications for SRLs within daily usage contexts, like enabling new perceptions, commuting and communication methods as well as enhancing existing ones. Yet, several requirements need to be met before SRLs can be widely adopted, such as multipurpose design and adequate sensory feedback. We discuss how these findings influence the design of future SRLs.

Author Keywords
Supernumerary, Robotic, Limbs, SRL, Augmented

Introduction
Supernumerary Robotic Limbs (SRLs) is a field in robotics and wearables that is concerned with the design and development of wearable robotic limbs that augment the human. Unlike prostheses that replace biological limbs, and exoskeletons that are mostly passive and enhance existing capabilities of humans (e.g., allowing users to jump higher [1] to travel faster [2]), SRLs are kinematically independent of the human skeletal structure [18]. SRLs are

1. The moderator asked "*If there were no technological constraints, what would be use cases for SRLs?*" Participants wrote down and/or sketched the use cases (see Figure 1).
2. After the number of use cases bottomed out, the moderator asked "*How would SRLs help in daily activities (e.g., when you wake up, prepare coffee, go to work, etc.)*".
3. After ≈20 min., the moderator asked: "*What would be requirements of SRLs (e.g. in terms of aesthetics, form factor, placement, morphology, etc.)*".
4. After ≈15 min., the moderator asked "*What would be nice to feel/not feel through SRLs (e.g. temperature, weight, textures, etc..)*".

Figure 2: The main questions that were asked in the focus groups.

Figure 3: One of the focus groups

wearable robots in the form of limbs that actively perform tasks similar to or beyond natural human capabilities (see Figure 1). Examples from research include supernumerary robotic arms [6, 9, 16], hands [7] legs [18], and fingers [22]. While there is a large body of work within SRLs and human augmentation communities, 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. Moreover, the majority of work focused on industrial applications that had well-defined contexts. As a result, the dynamic daily interaction context [4, 20], which affects the overall design of an interaction experience, is mostly neglected in previous work.

In Robotics research, 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, emphasizing physical interactions with surrounding environments [7, 18, 22]. SRL-control methods included flexion-sensor gloves [22], EMG [16], ring mounted buttons [11], and programming by demonstration [7].

One of the few works about SRLs in HCI is the work by Leigh and Maes [16] who investigated a wrist-worn morphological robot that provided different interaction capabilities. Their prototype allowed interaction with physical objects (e.g., it can morph into a grip that can carry buckets). Their prototype was controlled via electromyography (EMG) signals detected through an armband.

In this work, we provide the first steps in bridging the gap between HCI and the field of SRLs. Through focus groups, we collected use cases and requirements for SRLs that emphasized their regular use within daily interaction contexts. We contribute (1) 169 use cases for SRLs, clustered into 11 categories, and (2) 7 requirements that SRLs need to achieve in order to meet the users' expectations.

Focus Groups

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 (Mean = 28.7; SD = 10.8). All participants were familiar with SRLs either through sci-fi media or research literature. We prepared three main questions: (1) How can SRLs help in daily activities? (2) What are the requirements of SRLs? (3) What do users want to / do not want to feel through SRLs?

After filling a consent form and a demographics questionnaire, the moderator introduced SRLs by explaining the concept with figures and videos from related work [6, 9, 11, 16, 22]. The procedure and exact questions that were asked are shown in Figure 2. Each focus group lasted for 90 minutes. The sessions were recorded for post-hoc analysis. We collected all descriptions and sketches, then clustered and documented the use cases and requirements.

Use Cases

From notes and audio recordings, we extracted 169 use cases. These were then clustered into 11 categories by two researchers. Some were clustered into further subcategories. Tables 1 and 2 summarize the categories, subcategories, and how many use cases fall into them.

Basic physical interactions covers 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) [12, 14]. An interesting subcategory was *Manip-*

Category	Count
Basic physical interactions	**48**
– Strengthening	5
– Reachability	11
– Multitasking/efficiency	28
– Automation	4
Daily Activities	**30**
– Manipulating and Morphing into tools	11
– Interaction with digital content	5
– House chores	4
– SRL as a smart device	4
– Eating	2
– Hygiene	1
– Other	3
Complex/work-related tasks	**19**
– Manipulating work related tools	2
– Operating vehicles	3
– Others	14

Table 1: *Basic physical interactions* covered generic use cases where participants expressed how SRLs can extend their physical abilities. The *Daily activities* category was inspired by work from Gerontology. *Complex and work-related tasks* are tasks that normally require practice or can be done only by experts.

ulating 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 [19, 21].

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 prostheses. 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).

Requirements and Discussion

We present and discuss the requirements collected from participants by answering question 3 (see Figure 2).

Multipurpose Use

Analysis of both use cases and requirements indicate that being multipurpose is a core requirement for SRLs. This aspect is in line with previous work about wearable devices [8, 15, 16]. We further classify this requirement into:

(1a) **Morphological Design and Context Awareness:** the overall shape of SRLs should change to fulfill different contextual requirements (e.g., morph into a tool).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).

(1b) **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.

Category	Count
Perceptions	**16**
– Enhance current senses	10
– Add novel senses	6
Commuting	**9**
– Enhancing existing commuting methods	7
– Enabling the user to reach new places	2
Augmenting human-to-human interactions	**10**
– Enhancing existing communication means	7
– Enabling new means of communication	2
– Augmenting interactions with kids/babies	1
Personal care	**14**
Safety/Self-protection	**14**
Supporting the disabled	**4**
Augmenting sports and creative tasks	**3**
Enhancing human aesthetics	**2**

Table 2: This table augments Table 1 with another set of categories. Participants provided interesting insights into how SRLs can augment existing skills or enable achieving what is other-wise infeasible.

Previous work recommended that SRLs to serve multiple purposes [16]. Besides confirming that users find this important, 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 [16], we found that fully autonomous SRL tasks are desired (e.g., cooking or driving).

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 SRLs should support:

(2a) **Controlled Sensory Feedback:** participants mentioned they would like to feel the SRL's state. For example, they want to feel the degree at which SRL-joints are bent (similar to proprioception). They also wanted to feel the environment through the SRL (e.g., feeling a surface's texture). However, they would rather filter extreme sensations (e.g., temperature when the SRL touches a hot pot). Sensory augmentation by substitution [3, 17] was suggested (e.g., translating temperatures to different levels of haptic feedback). Thus, sensory feedback should be available and controlled in terms of intensity and type.

(2b) **Enhanced Perception:** SRLs should not only enable but also enhance user's perceptions. Examples include equipping an SRL with a camera for endoscope-style controls, auditory perception enhancements to filter and listen to certain frequencies, and olfactory sense extensions to protect from harmful gases.

(2c) **Novel Senses:** participants reported that SRLs should additionally enable novel senses. Examples include built-in sonars that allow navigation in the dark, automatic detection of people's emotions, and sensing chemical-substances sensors to, for example, detect food tastes.

Design of SRLs

We found that participants rather regard *sensing* and *perception* as well 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 (Table 2). Participants also reported non-functional requirements:

(3a) **comfortable to wear and use**. Similar to artistic works [13], SRLs should be ergonomic, easy to wear and take off, comfortable, and lightweight.

(3b) **aesthetics and anthropomorphism**. SRLs should be personalizable in terms of colors, designs and features. Robot-like limbs were mostly preferred over Anthropomorphic limbs (i.e., human-like limbs [5, 10]) by our participants, citing reasons such as being "creepy", "scary" and "unnatural". Interestingly, one participant preferred human-like limbs and found robot-like ones to be "scary".

Conclusion and Future Work

The results of the focus groups revealed many inspiring use cases, and expectations from SRLs. We provided a categorization of use cases, in addition to a set of requirements that can guide SRL development in the future. We discussed how our results compare to previous work, identified novel requirements, and confirmed that some existing ones are also desired by users. In the future, we intend to investigate additional factors, especially those related to SRLs' shape, morphologies and anthropomorphic characteristics. We plan to further our approach by diversifying our evaluation approaches, such as by carrying out workshops, surveys and user studies using SRL prototypes.

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