Social Digital Cyborgs: The Collaborative Design Process of JIZAI ARMS

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Figure 1: Two people wearing the JIZAI ARMS exchanging a robotic arm.

ABSTRACT

Half a century since the concept of a cyborg was introduced, *digital cyborgs*, enabled by the spread of wearable robotics, are the focus of much research in recent times. We introduce JIZAI ARMS, a supernumerary robotic limb system consisting of a wearable base unit with six terminals and detachable robot arms controllable by the wearer. The system was designed to enable social interaction between multiple wearers, such as an exchange of arm(s), and explore possible interactions between digital cyborgs in a cyborg society. This paper describes the JIZAI ARMS' design process, an interdisciplinary collaboration between human augmentation researchers, product designers, a system architect, and manufacturers, to realize a technically complex system while considering the aesthetics of a digital cyborg. We also provide an autobiographical report of our first impressions of using the JIZAI ARMS and use our findings to speculate on a model of potential social interactions between digital cyborgs.

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CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**.

KEYWORDS

Human Augmentation, Cyborgs, Digital Cyborgs, Social Digital Cyborgs, Human-machine Integration, Human-computer Integration, Robotics, Human-robot integration

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1 INTRODUCTION

"I can let you have one of my arms for the night," said the girl. She took off her right arm at the shoulder and, with her left hand, laid it on my knee.

This is the beginning of "*One Arm*," a short story written by Nobel Prize-winning author Yasunari Kawabata in his later years (1963-1964). In this short story, a man is caught staring, enamored by a girl's beautiful arms. The girl then decides to lend him her arm for the night. Kawabata proceeds to vividly describe the confusion experienced by the man as he passes the night with the girl's separated arm, at some point even going as far as replacing his own arm with the girl's. This novel is obviously a work of fiction, yet, half a century since its writing, emerging human-machine integration technologies (e.g., [30, 48, 51, 55]) have begun to allow us to physically experience Kawabata's world.

In this paper, we speculate on the experience of having (machine-made) shareable body parts. In particular, we explore human behavior and interactions which result from acquiring removable and exchangeable body parts. We conduct this speculation by first designing a modular supernumerary robotic arm system called "JIZAI ARMS" (Figures 1 and 2). It consists of a base unit with six terminals where custom-made robotic arms can attach, and an associated set of robotic arms. The system allows a wearer to attach, detach, replace, edit, and alter the arms that they wear while the system is online. Namely, given multiple people with the system, a wearer can exchange, gift, or be gifted arm(s) by another wearer. Finally, the system is equipped with enough connectivity that it could allow a wearer to operate the extra arms in any way they wish.

Emerging technologies, such as robotics, machine learning and various aspects of HCI are of great importance to research into supernumerary robotic limbs (SRLs) [10, 60, 63, 71]. Research on how human and body augmentation technologies affect and transform the wearers' own "body images," cognition, and even brains (e.g., [2, 81]) are similarly crucial as SRLs technologies mature and move towards seeing use in society. In contrast, there are few discussions on the social aspects of SRLs. This is despite humans being social animals who need to coexist with others. They attract and communicate with others through physical expression, communication, and performance. There is a need to investigate how artificially acquired body parts shift one's approach to communication or what detachable SRLs, especially detachable ones, bring to multi-person interactions. By designing and conducting social interactions with JIZAI ARMS, we seek to understand interactions that occur between multiple digitally-augmented humans or "digital cyborgs" [30]. By doing so, we hope to predict the near future in which people freely and flexibly adopt human-machine integration technologies and make use of them in social settings.

This research addresses three design issues:

(1) Aesthetics of a Digital Cyborg Body: The design of a beautiful, desirable JIZAI ARM, both as a stand-alone device and as a part of a living human being.
(2) Attachability, Detachability, Exchangeability, and Shareability Functions: The design of actions and interactions such as attaching, detaching, and exchanging.
(3) Social Interactions with JIZAI ARMS: The design of social communications, interactions, and activities people using the JIZAI ARMS could engage in.

To tackle these issues, we (the authors) gathered a specialized team consisting of members from a variety of backgrounds including human augmentation researchers, product designers, a system architect, and manufacturers. In this paper, we applied autobiographical design research [12, 13, 29, 70, 83] and focused on the exchange of knowledge between experts of different specialties through intensive discussions and collaborative design and engineering activities as well as our first impressions on acquiring JIZAI ARMS and interacting with people with JIZAI ARMS. This autobiographical account provides readers with important insight into how researchers, designers, and engineers can collaboratively design and produce a human-machine integrated system as a digital cyborg. We believe this to be of great value, as there is currently no well-established way to produce such a system.

Our design research process (the main content of this paper) consisted of 5 aspects: 1) Literature review, 2) Concept construction, 3) Design and development process, 4) Role playing based on the concept, and 5) Discussing "social digital cyborgs."

In 1), we comprehensively reviewed the existing research related to JIZAI ARMS and investigated research opportunities by writing a literature review. In parallel, in 2) we collaboratively created the concept of JIZAI ARMS through discussion and sketching, and constructing research questions we could investigate using it. To specify the research questions and clearly define the concept, we also wrote a textual description of the concept that included scenarios JIZAI ARMS wearers might enact to interact and communicate each other. This provided us with material to further our discussions on our research questions. Then, in 3) we moved onto designing JIZAI ARMS in detail. Our team intensively discussed, designed, and finally built a base unit and set of arms which constituted an initial prototype of JIZAI ARMS. Throughout the design and manufacturing process, we took care to be constantly aware of how JIZAI ARMS would generate the experience defined in the textual description. After the development phase, in 4) we took it upon ourselves to role-play the scenarios detailed in the textual description with JIZAI ARMS to acquire embodied impressions. Finally, in 5) we speculated on the kind of social life digital cyborgs

Figure 2: A digital cyborg wearing a set of JIZAI ARMS freely moving the worn robotic arms.

with shareable body parts might experience. In this paper, we describe the design process of the JIZAI ARMS, and provide a vivid report on how it feels to have JIZAI ARMS as the first people to acquire and use them. We also provide a comprehensive discussion about what we learned from physically making the JIZAI ARMS and socially communicating while wearing them.

2 LITERATURE REVIEW

2.1 Digital Cyborgs and Supernumerary Robotic Limbs

Scientists have envisioned augmenting the human body utilizing machines for a long time. In 1960, Manfred E. Clynes and Nathan S. Kline coined the term "Cyborgs" in the article "Cyborgs and Space," a portmanteau of Cybernetics and organism, and defined it as an "*exogenously extended organizational complex*." They used this term in the context of space development to refer to a man-machine system capable of assisting in the maintenance of a human's homeostasis in new environments [8]. They illustrated the idea with a realistic example, a small infusion pump embedded into the body which could be used to control blood pressure.

The term "cyborg" has since seen widespread use and now typically refers to organisms with electro-mechanical elements that extend their abilities. Cyborg technologies have evolved to include a variety of methods of physically altering or transforming human bodies. While these technologies have typically been invasive and permanent, in recent years, wearable devices have been utilized to produce a new kind of transient cyborg. In this paper, we refer to this new kind of cyborg as a "digital cyborg."

While the term "digital cyborg" was initially used by Deborah Lupton, referring to a human augmented by their use of digital media technologies [45, 46], we use it here with a broader meaning, as in [30]. In particular, we use the term to refer to a human who has undergone augmentation through the use of non-invasive technologies. This results in a kind of virtual human body augmentation which does not physically modify the natural body but results in an augmented state. Many recent works have begun exploring this approach to human augmentation due to the limited risk of transferring to a cyborg. For instance, researchers have developed systems that enhance one's sense of sight [26, 32, 34], smell [6], vocalization [3] and manipulation [79] using non-invasive augmentations.

Since around the 2010s, robotics researchers investigating human augmentation have specifically begun focusing on augmenting one's physical capabilities using wearable robotic limbs, supernumerary robotic limbs (SRLs). Initially, such works focused on applying SRLs to industrial settings where it is difficult to deploy larger, fixed-base robots [62]. For example, Parietti et al., who introduced the concept of SRLs, proposed the idea of wearable robotic arms that work independently from one's natural limbs to support industrial workers during construction or airplane assembly [61, 62, 64]. Since the publication of these initial works, a research community developing and studying SRLs has been growing, especially in recent years [15, 68, 80, 88]. Currently, a variety of types of supernumerary robotic appendages, not only limbs, have been proposed. These include fingers [67, 87], tails [49, 56], as well as upper and lower limbs.

Regardless of the type of supernumerary robotic appendages, an important research question is how one should control the additional appendages. A range of approaches have been proposed to date to achieve a variety of augmentation experiences. For example, researchers have proposed remapping the motion of feet [71, 73], making use of redundant degrees of freedom in the body (e.g., the shoulders while the hands are fixed [75] and the fingers while holding an object [22]) to control robotic arms to give wearers the sense of possessing additional arms. Others have proposed having the robotic arms be controlled by another person (i.e., not the wearer) to make it seem as if two people had joined together in a single body [71]. In this way, SRLs (and digital cyborg technologies in general) can allow one to experience states that are typically unachievable with a natural human body.

Going further than wearable technologies or physical hardware development, virtual reality technologies can allow one to experience even stranger states of being a digital cyborg. As a non-invasive approach to augmenting how one experiences the world and themselves, virtual reality can be counted as a technology that allows one to become a digital cyborg. Its unparalleled freedom, unfettered by the laws of reality, allows it to further expand the scope of possible digital cyborg experiences. This includes providing the experience of acquiring virtual robotic limbs (e.g., [2, 18, 30, 38]), having an invisible body [39], consisting of separated body parts [37], or even having duplicate bodies [52]. Using these Virtual Reality (VR) techniques to produce virtual digital cyborgs, scientists, especially in the areas of cognitive science and neuroscience, have recently begun research into digital cyborgs and exploring how humans can learn to accept bodies modified by technology and how they adopt to life as digital cyborgs.

2.2 The Science of Digital Cyborgs

In 1998, Botvinick and Cohen published work indicating that it may be possible for humans to embody an artificial body part [5]. This seminal work heavily influences research done today on how humans may adopt modified bodies. The phenomenon that they discovered is named the "rubber hand illusion" and refers to a subject feeling as if an artificial rubber hand is their own. This illusion is induced by synchronized visual and tactile stimulation. In their experiments, Botvinick and Cohen had subjects watch an exposed rubber hand being stroked with a brush while their own, hidden, hand was stroked at the same time. After being exposed to the visual-tactile stimuli, the subjects tended to feel that the rubber hand was their own. This experiment indicated that a human can feel a sense of body ownership, which is one of the components of the "minimal self" proposed by Gallager [19], towards an artificial and substitute body part.

As already mentioned, rapidly evolving immersive VR technologies have spurred on research into the effects of more exotic body augmentations in recent years. For instance, researchers have explored whether people are able to adopt augmented bodies with lengthened arms, a transparent core [39], scrambled hands and feet [37], shared with another person [17, 24, 77, 78], and additional body parts. Research on the effects of being in an animal body avatar structurally different from a human, such as a tiger, a spider, a bat [41], a scorpion, a rhino, and a bird [40] has also been conducted. The flexibility in body representations that humans can adapt to has encouraged researchers to explore whether one might be able to acquire a completely new body which could not have been created without the use of technology.

SRLs are one example of such an exploration. Scientists focusing on SRLs have been exploring whether the acquisition of supernumerary limbs is possible (both physically and mentally). Because humans make frequent use of their upper limbs and hands in daily life, supernumerary upper limbs in particular have been the subject of considerable research. Previous studies have suggested that humans can have a sense of body ownership towards supernumerary body parts similar to the ones used in our study (JIZAI ARMS). For example, Ehrsson et al. indicated that a subject can have a sense of body ownership towards two rubber right hands placed side by side on a table at the same time [16]. Guterstamy et al. conducted a similar experiment applying synchronized visuotactile stimuli to a subjects' natural right hand and a right rubber hand, placed side by side on a desk within sight of the subject [23]. They reported that the subjects could feel a sense of body ownership towards both their natural and rubber right hands. Newport et al. further showed that a human can feel a sense of body ownership not only towards two stationary hands but also two moving hands [57]. Most recently, Arai et al. [2] investigated the embodiment of a virtual human avatar wearing two supernumerary robotic arms in an immersive VR environment. The subjects felt that they acquired the two robotic arms controlled by their foot motions. These results indicate that humans may be able to become a digital cyborg using wearable robotic arms.

This places the digital cyborg in quite an attainable position. Following up on the expectation of humans becoming digital cyborgs in the near future, through our work, we add another aspect to speculations on digital cyborgs of the near future: how humans may use their augmented bodies in human-human interactions. This contrasts to previous research, which has primarily focused on the first-person experience of being a digital cyborg. As digital cyborgs become more involved in society, understanding how not only the digital cyborgs themselves but also those who interact with them (whether they are also digital cyborgs or not) will accept the digital cyborg will help human augmentation researchers to design digital cyborgs in the future. To speculate on the future of a digital cyborg society, we designed our system with a strong emphasis on human-digital cyborg interaction and multiple digital-cyborg interaction.

2.3 Designing Digital Cyborgs and Exchangeable Human Body Parts

The replacement of one's arm or leg with an artificial one to obtain new functions, a scenario that has been depicted in the world of fiction, is becoming a reality today. We can see it in para-sports. Athletes who have lost part of their lower limbs will have their leg replaced with a prosthetic leg optimized for the sport and the athlete for the duration of the competition. Thanks to the athlete's tireless efforts, they master the prosthetic leg and use its improved performance to achieve records that surpass the records of athletes without prosthetic legs [14].

Nowadays, thanks to advances in robotics and VR technology, it is becoming possible for people who still have their natural body parts to experience detaching, attaching, and exchanging body parts. For example, Iwasaki et al. proposed the concept of a "detachable body," in which a third and fourth robotic limb is attached to the human body and can be detached freely [33]. The user of a detachable body would be able to use the robotic arm in multiple remote locations, detaching the robotic arm and securing it to the environment as needed. In addition, many studies on supernumerary robotic upper limbs have proposed that the end of the arm be replaced with the appropriate one depending on the application at hand.

VR technology and wearable SRLs have also enabled the experience of sharing a body with another person. Saraiji et al. created the experience of two people sharing a single body by developing two wearable robotic arms designed to be remotely operated by another person [72]. Takizawa et al. recreated a similar experience in a VR space to investigate the effect of the perspective provided to the remote person [78].

More recently, researchers have begun to study the effect attaching and detaching body parts has on humans. Hammad et al. defined the cyborg state as the state in which a person wears SRLs, and focused on the cognitive and mental load of transitioning between the normal state and the cyborg states. They designed a protocol to reduce the cognitive and mental load humans experience when they enter or leave the cyborg state and to facilitate the transition [25]. They reported that wearers lost the sense of security they gained when they entered the cyborg state upon leaving it.

Other works have focused on how digital cyborgs are perceived by an outside observer. Ladenheim et al. [42] explored how others perceive a digital cyborg through creative expression. In their stage performance featuring a female cyborg with wearable robotic wings, the authors reported that the audience interpreted the performer's emotional state by linking it to the motion of both the performer's body and the robotic wings.

Non-invasive technologies enabling digital cyborgs like SRLs not only affect the one who is transformed, but also leaves an impression on and can affect others who observe and live with him/her. Beyond the task-oriented approach to developing cyborg systems, such technologies are being applied in a wide range of contexts in everyday life, such as telepresence, detachability, and stage performances.

This paper mainly contributes to the human augmentation research community, with a strong focus on digital cyborgs enabled by SRLs, by speculating on social interactions between multiple digital cyborgs. By documenting our design process, we also contribute to the CHI community with a case study of research through design (RtD) [89] by providing insights that can be referred to in future design projects considering the development of human augmentation technologies. Our tangible and working prototype presented in this paper is designed as a research product [59] that not only speculates on our concept of the social digital cyborg but also enables humans to physically experience the concept. We believe that our autobiographical report [12, 13, 29, 70, 83] through the role-playing will support these researchers in contributing to the development of social digital cyborgs.

Although there are few past works which position aesthetics as a strong point of concern in designing robotic human augmentations or digital cyborgs, we strongly emphasize the importance of designing the aesthetics of a digital cyborg for a digital cyborg society. As the associated technologies approach maturity in terms of practicality, careful design of their aesthetics will be essential for their social acceptance and integrating them into peoples' everyday lives, beyond the research laboratory. This paper begins to discuss the aesthetics of artificially made (robotic) human bodies beyond the scientific understanding of digital cyborgs and task-oriented or usability studies. This aesthetics not only includes the beauty of the JIZAI ARMS as a product but also the wearer's bodily movements and his/her subjective somatic senses. Though it is difficult to precisely articulate all issues raised here, we present the topics for future discussions regarding the aesthetics of digital cyborgs.

3 METHODOLOGY

3.1 An Autobiographical Study Investigating Social Digital Cyborgs

We adopted an autobiographical approach to document our research for several reasons. Our collaborative development process critically documented [70] in this paper—that provides insights for future design projects developing human augmentation systems, especially social digital cyborgs—was an intensive one and took place over a long period of more than half a year. We thought that an autobiographical recording would reveal findings from our activities across all our design processes that are usually hidden and not documented in a research paper [12, 13]. The design process also included iterative reflections [83] through discussion, sketching and drawing, designing using computer-aided design (CAD) tools, software coding, hardware sketching, and so on [7].

It was far from a waterfall development and was achieved through close interdisciplinary collaboration based on Design Thinking [9, 65]. This is because our team (described later in detail) consists of researchers, engineers, and designers. Some team members have expertise in design-led developments, but the others do not. Thus, we carried out this project by applying Design Thinking methods to synthesize various knowledge and to facilitate collaboration in the team. To design the JIZAI ARMS to be a wearable robotic system for enabling social interactions, we sometimes tested early prototypes in not only virtual environments using 3D CAD software but also in physical environments through body storming to explore somatic or bodily experiences.

For this soma-based design process, we also referred to Höök et al. [28, 29]'s first-person's design approach and explored the soma-aesthetic interactions with the JIZAI ARMS. While the major traditional research on robotics (even in HCI contexts) mainly focuses on evaluating developed systems, our approach is to reveal how humans subjectively adopt robotic systems and what kind of social and interpersonal interactions happen between the wearers. Therefore we foreground the soma-aesthetic first-person's documentation in this paper.

Our subjective, reflective, and soma-aesthetic documentation aims at not only understanding the superficial form and appearance of the digital cyborg enabled by the JIZAI ARMS but also how one may adopt and accept extra body parts and acquire an altered body image. To investigate this, we focused on subjective and reflective impressions of the JIZAI ARMS' wearers in our autobiographical research process, referring to Rapp [69]'s internalistic understanding of wearable technologies.

Our autobiographical record, which serves as our primary data in this paper, is mainly divided into two parts; 1) a record of the collaborative design process that was carried out by the interdisciplinary team (between the authors) and 2) a record of the authors role-playing with the completed system. The former part illustrates how we designed the JIZAI ARMS to be an integrated social digital cyborg system. The latter part reports on our initial impressions, gathered from various professional perspectives, from participating in social digital cyborg interactions. The role-playing sessions can be defined as a body-storming reflective design process, not only for improving the current JIZAI ARMS prototype in the near future but also for developing future social digital cyborgs in general.

3.2 Collaborative Design Process

To investigate soma-aesthetic interactions through the digital cyborgs in this research, we believed that we would need to create not only a technically functional and integrated system, but also an aesthetically beautiful one. To achieve both requirements, a team with a wide range of expertise with prior experience in related areas was gathered from numerous backgrounds and was tasked with realizing the concept. The team consisted of human augmentation researchers, product designers, a system architect, and a manufacturing company. Throughout the design process, the team needed to reach a mutual understanding of the fantastic visions, overcome interdisciplinary barriers, and fill each others' gaps in understanding to achieve progress. What follows is a detailed description of the members:

(1) *Human augmentation researchers (HARs):* These members were researchers specializing in the domain of human augmentation. Their work overlaps with research in many other areas including computer science, VR technology, and robotics. They had experience conducting research related to wearable supernumerary robotic upper limbs and human-machine/robot mutual action. In the design process, they proposed and refined the overarching concept that would be acted out with the JIZAI ARMS. They led and managed the design project.
(2) *Product designers (PDs):* These members specialized in introducing aesthetic elements of product design into areas where particular design methods have not yet been established. Many of their works are dynamic and involve motion, such as applying organic elements (e.g., bio-inspired forms and motion). They also have experience in designing prosthetic upper and lower limbs. In this project, the HARs sought to make not only the robotic arm itself, but the whole (including the wearer) aesthetically appealing and consistent, both when static and when in motion. As such, the PDs were tasked with the primary design of the JIZAI ARMS: the styling design and the layout of key electrical and mechanical components.
(3) *System architect (SA):* The SA had design experience relating to integrating aesthetics and mechatronics into a product. One of his roles was bridging between the design concept and the manufacturing of the JIZAI ARMS. When a conflict arose between the aesthetic requirements and the manufacturing or structural capabilities, he proposed substitute ideas that both sides could agree on. He was also responsible for designing the system architecture which fulfilled the system requirements. He additionally selected key off-the-shelf parts, such as motors, gears and controllers, and designed custom components when off-the-shelf components did not meet the system requirements.
(4) *Manufacturing company (manufacturer):* The manufacturer has significant experience realizing new design concepts into working prototypes (e.g., realizing a concept car for a motor show). To realize the JIZAI ARMS into a tangible form while respecting the original concept, the manufacturers needed to be familiar with both the concept and a wide range of manufacturing methods. They were in charge of the detailed mechanical design, manufacturing of mechanical parts, and assembly (including electric wiring). They were invited into the team to manufacture a functional prototype of the JIZAI ARMS after the detailed concept was fixed.

The collaborative design process was highly iterative, involving many discussions, and full of first-time endeavors for all those involved. For example, the HARs had experience developing concepts, but not to a level of polish required for this project. Similarly, the PDs, the SA, and manufacturing company all had experience designing and creating polished products with electromechanical components, but not for the purpose of realizing social digital cyborg interactions or even human augmentation in general. Following the design process, the team experienced their own transformation into digital cyborgs and conducting the first ever social digital cyborg interactions through the role-playing sessions.

3.3 Role-playing by the Design Team

In the role-playing sessions, the team experienced a prototype of the JIZAI ARMS, and followed the textual description of the concept defining interaction patterns and scenarios for the JIZAI ARMS (described in the next section in detail). The main purpose of the role-playing was to allow the authors to experience the JIZAI ARMS, record their first impressions, and explore implications which may facilitate future researchers seeking to improve the JIZAI ARMS and to study social digital cyborgs.

Role-playing sessions were conducted over two days. The first-day session was conducted for three hours in a mirrored dance studio so that the wearers could see their own bodies carrying a prototype of the JIZAI ARMS. The participants experienced seeing the four arms moving using a controller. They saw the arms moving both on their own bodies and on others' bodies. The objective of this first session was to have the team wear the JIZAI ARMS they developed for the first time, operate the robotic arms of others, operate the arms themselves, experience attaching and detaching the robotic arms, and to document the experience in detail (Figure 9).

The second-day session was held in a room in the building where the HARs' laboratory is located. The room was simple with no mirrors. As the team already had the experience of looking in a mirror while wearing the JIZAI ARMS on the first day, the second day focused on allowing participants to concentrate on their own sensory perception without relying on mirrors.

3.4 Data Collection

Our autobiographical data was recorded in several media formats, including as text, sketches and drawings, photos, videos, sounds, 3D modeling data, etc. These media were shared and archived on multiple online tools/platforms such as Google Drive, Slack, Miro and Jamboard (online whiteboard services), Zoom, and e-mail. The main source of the descriptions that appear in this paper was a research diary with photo and video attachments (captured during the design and development process and the role-playing sessions). The diary was shared as a Google Document and as Slack channels to the HARs, PDs, and the SA. To describe the design sessions in this paper, the first author mainly highlighted relevant content from the diaries, prepared written drafts, and revised them through online discussions with the other authors.

To capture a complete account of the role-playing sessions, all participants were asked to share their impressions in the diary. Additionally, after the second session, an online discussion session was held wherein the recorded videos were replayed and individual impressions were discussed. The video recordings of the role-playing and discussion sessions totaled approximately eight hours in length. The videos recorded were transcribed for analysis. We conducted a qualitative analysis of the transcripts [20]. Specifically, we first sorted the transcripts by the two themes: 1) senses and impressions of wearing the JIZAI ARMS and 2) social interactions using the JIZAI ARMS. After this, we found more detailed themes and reflect on them in the subsections in Section 5. The themes compose the key ideas which should be considered when designing future digital cyborgs. By referring to multiple autobiographical data sources, we not only aimed to precisely reveal hidden elements of the design process [13] but also illustrate the soma-aesthetic impressions [28, 29] of the JIZAI ARMS.

4 DESIGN PROCESS

4.1 Concept Construction

To design the concept of the JIZAI ARMS, the HARs, PDs, and the SA continuously discussed and elaborated on abstract images of the JIZAI ARMS while making the textual description of the concept and sketches. This process was conducted in three phases; 1) describing the concept, 2) sketching an image of the JIZAI ARMS as a product, 3) sketching how humans may move and perform while wearing the JIZAI ARMS.

4.1.1 Defining a textual description of the concept. In order to explore the social interaction of digital cyborgs, the HARs first attempted to draft a textual description of what they wanted to achieve with the JIZAI ARMS. In making this description, they focused on interaction/communication patterns and scenarios which would be enabled by acquiring a set of JIZAI ARMS. The textual description written below, inspired by Kawabata's novel quoted in this paper's introduction, was gradually revised and updated throughout the design process. Many patterns and scenarios were imagined and discussed over several brainstorming sessions, but the ones listed below were eventually selected to be the core scenarios. They were selected because the focus of our study was to understand how humans acquire attachable, detachable, and exchangeable body parts to become digital cyborgs. Given a limited research budget, we built a set of JIZAI ARMS prototypes that allowed us to explore our research questions as defined in the patterns and scenarios below.

(1) *Aesthetics of a Digital Cyborg*: JIZAI ARMS should harmonize with the body of the wearer. The wearer should feel as if the robotic arms are an extension of his/her body, despite them not looking like biological body parts. Another person who sees a JIZAI ARMS wearer should receive the impression that the arms extend from the body of the wearer instead of being worn like a back pack. The robotic arms should harmonize with the wearer's natural arms, such that an observer would feel the wearer is an integrated digital cyborg who is one with the JIZAI ARMS. Once separated from the wearer's body, the robotic arm should be seen as a part of the (former) wearer's body.
(2) *Attachable/Detachable Experience*: JIZAI ARMS should be smoothly and immediately attachable and detachable from the wearer without the need for any specific tools, while the arms are working. The robotic arms move as a part of the body of the wearer right after being attached. The robotic arms, when detached from the wearer's body, may be stretched out, lifeless, and heavy or still twitch like separated living body parts. Additionally, the attachment position of the robotic arms should be flexible.
(3) *Exchange Experience*: The HARs sought to realize a situation in which two persons wearing JIZAI ARMS meet. In this situation, wearer-A wants to borrow one of wearer-B's arms because wearer-A finds wearer-B's arms attractive. Wearer-A detaches them from wearer-B and passes them to wearer-B. Wearer-B then attaches them to the back of wearer-A. The robotic arms become animated and start to work as wearer-A's arms. Our teaser figure (Figure 1) was derived from this scenario.

By continuously sharing our understanding of and updating the textual description of the concept within the design team, efforts were made to establish a common understanding of what was to be developed. Following this common understanding, each member worked towards developing a product that could realize the textual description by applying their area of expertise.

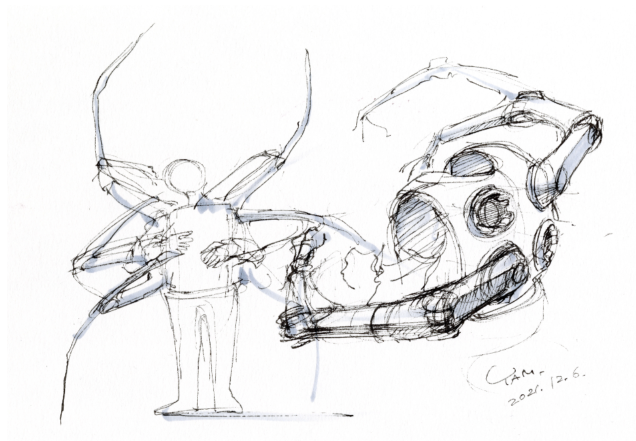

Figure 3: The initial concept sketch of the JIZAI ARMS

4.1.2 Sketching a static vision of JIZAI ARMS. While defining the textual description of the concept, the HARs, PDs, and the SA collaboratively illustrated visual concept sketches of JIZAI ARMS. To sketch the JIZAI ARMS, the HARs first introduced the other team members to previous research on SRLs (e.g., [21, 44, 73]), and clarified the differences between the JIZAI ARMS and these previous works. They highlighted that the previous studies focused on the first-person perspective of the wearer. Namely, that their appearance is that of a typical mechanical robot and they work to emphasize human-"machine" integration (e.g., [4, 84]). The HARs noted that JIZAI ARMS, in contrast, emphasize "oneness" with the wearer.

During the discussion following the HARs' review of the literature, one of the PDs made a sketch, (Figure 3). The sketch included a set of SRLs that emphasized unity with the wearer's body and demonstrated the PD's understanding of the concept that the HARs had conveyed. The PD who made the sketch suggested that the JIZAI ARMS should have a form similar to that of an armored vest to be united with the trunk of the wearer, as shown on the right side of Figure 3. In the concept sketch, the robotic arms sprout from the back of the armored vest. A discussion on where and how many arms should be allowed led to an agreement that four to six bilaterally symmetric arms should be considered. Symmetry was agreed upon due to the need for balance. It was suggested that a asymmetric design could put unwanted strain on the wearer's

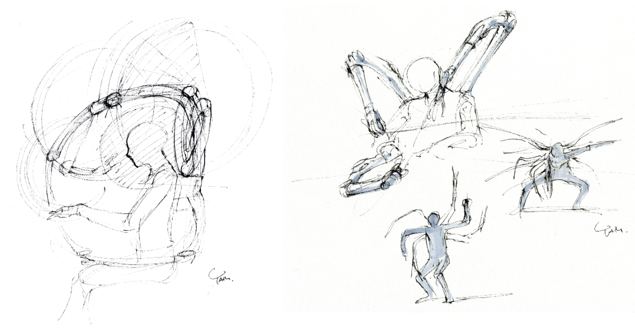

Figure 4: Sketches from when the PDs considered various movements with the JIZAI ARMS

body. It was agreed upon to consider at most four to six arms as the area of the average person's back was deemed too small to accommodate eight or more arms of average thickness, especially when considering additional mechanisms would be needed to keep the robotic arms in place on the back. Further discussion on mechanics of the arms evolved the concept to include a limb section between where it attached to the body and the upper arm. This was added to allow the end of the arm to achieve the same reach in front of the wearer despite its attachment point on the back of the body. At this point, the PDs suggested that, since the robotic arms were to be detachable, a mechanism that mechanically changes the mounting angle of the robotic arms when fixed to the terminal would be beneficial. It was suggested that this would allow an arm's range of motion to be changed to suit the application, making the JIZAI ARMS more versatile.

4.1.3 Sketching the JIZAI ARMS in Motion. To add further details and flesh out the initially sketched concept (Figure 3), the team discussed potential motions and interactions that might result from digital cyborgs with the JIZAI ARMS. HARs suggested that the robotic arms should be usable for bodily creative expression (e.g., [42]), such as dance performance, in addition to practical tasks, such as picking up or holding objects (e.g., [44, 73]) to emphasize the need for an aesthetically harmonious digital cyborg. They also suggested that creative expression through a cyborg body might be an effective means of exploring how people perceive digital cyborgs from a third-person perspective. Inspired by this suggestion, one of the PDs made a sketch to share how they imagined a wearer of the JIZAI ARMS performing various motions (Figure 4). After seeing the sketches, the HARs, PDs, and the SA recognized that there was a need to examine a wide variety of poses, such as being tilted forward (the right middle image of Figure 4), and extending the robotic arms with the natural arms of the wearer. There was also some discussion on the joint arrangements. Through the discussion it was agreed that whether or not the joint arrangement was the same as a human's arm would also affect the appearance of movement (Figure 5).

Variation on the hand modules attached to the end of the robotic arms were also discussed (Figure 6). The PDs had designed prosthetic arms in a previous project, so they suggested that three-fingered manipulators were easy to use for picking because they do not require precise fingertip orientation adjustment. On the

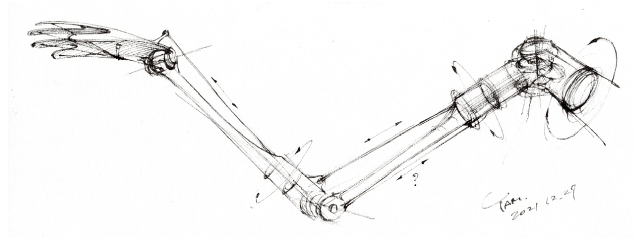

Figure 5: A sketch of a robotic arm with the same joint arrangement as a human's natural arm.

other hand, the shape of a five-fingered hand could give viewers a strong impression that the robotic arm is owned by a human. It was decided to prepare two types of hand modules for the JIZAI ARMS, a five-fingered hand for creative expressions and a three-fingered manipulator for practical tasks, each of which could be interchangeably attached to the end of the robotic arm.

Over the course of several discussions and sketching sessions, the team collectively decided upon the finalized primary concept of the JIZAI ARMS. Following the textual description of the concept, the robotic arm(s) needed to be able to be handed over and attached to another person. To meet this requirement, it was decided that the JIZAI ARMS would consist of two key components, a base unit, and robotic arms. The base unit would be worn on the wearer's body at all times and would have terminals that allow up to four or six robotic arms to be attached to the wearer at once. The robotic arms would be attached to and detached from the base unit quickly and without tools. Based on this primary concept, the team moved onto the development process: determining the technical specifications of the JIZAI ARMS.

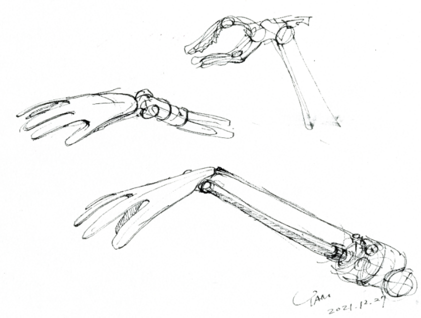

Figure 6: Considering the design of hand modules

4.2 Development Process

The development process consisted of not only developing integrated hardware and software for the JIZAI ARMS as a product but also designing how the wearer stands and performs as a digital cyborg with the JIZAI ARMS. In designing for the interactivity of the JIZAI ARMS, we followed design methods for interaction design [7, 54]. However, there were only a few references we could draw on for designing its soma-aesthetic [28, 29] and human-machine integrated [30, 50, 55] elements. As such, we took an explorative approach to the development process of the finer details and aesthetics of humans wearing the JIZAI ARMS.

Figure 7: The PDs are examining placements and angles of the JIZAI ARMS through rapid prototyping.

4.2.1 Configuration of robotic arms on the human body. After defining basic interactions and movements in the sketch, we discussed the attachment position and angle of the robotic arms to the base unit. The PDs prepared quick-and-dirty prototypes and iteratively investigated how arrangements of the arms impacted the load felt by the wearer and their appearance. The prototype consisted of aluminum pipes assembled into a square frame with additional backpack straps so that it could be used as a prototype of the base unit and other pipes representing the robotic arms (e.g., Figure 7). Assuming that a total of six robotic arms could be attached, they tried wearing a pair of pipe arms in each of the three pairs of attachment positions, the upper, middle, and lower, one at a time, and at varying attachment angles. We reflected these findings in the final design decisions as follows.

We decided to implement attachment points at all three positions we tried since we found that each position had its pros and cons. That means the JIZAI ARMS would have up to six robotic arms. We thought it important for JIZAI ARMS' wearers to have the flexibility to choose the position in which their arm is attached to fulfill their needs. For example, when performing a task that uses both a robotic arm and the wearer's hands in front of the wearer's body, the robotic arm should be positioned so that it does not interfere with the wearer's hands (e.g., in the lower position). On the other hand, in terms of creative bodily expression, we found that extending the pipe arms attached at the upper position allowed for expression that makes the entire body appear larger. The middle position could also be used to make it seem like the arms were hugging the wearer's body. In contrast, when arms were attached at the lower position, we found that care would be necessary to avoid collisions with the floor, especially when the wearer was short in height.

Additionally, we determined that it was desirable for the attachment angles of the robotic arms to be manually adjustable. This is due to different angles of attachment giving a different impression to the wearer. For instance, when the pipe arms were in the upper position reaching over the wearer's shoulders, the arms were frightening to the wearer because they were so close to the wearer's face. However, when the pipe arm was attached at an angle of about 45 [deg] diagonally or horizontally at the upper position, the wearer's sense of fear was attenuated because the pipe arms were away from the face. The attachment angle of the robotic arms was found to affect the visual impression of the wearer of the JIZAI ARMS as well. We noticed that the pipe arm attached in the upper position rising outward and upward from the shoulder gave the impression of the wearer having wings.

Different attachment angles of the robotic arms could also change their operability. The difficulty in manipulating the robotic arms at the lower position, as mentioned above, could be alleviated by changing the attachment angle.

This prototype further served to make the team aware of the changes in comfort caused by shifts in the center of gravity. When the pipe arms were at the top position and the center of gravity was shifted upward, the frame lifted off the waist. It was concluded that tightening the base unit to one's body at this position would be necessary for fitting the base unit.

4.2.2 Aesthetically harmonizing the JIZAI ARMS and the human body. The PDs also discussed the exterior appearance of the JIZAI ARMS and how they should harmonize with the human body. Although the JIZAI ARMS are composed of non-organic materials, the HARs requested that they harmonize with the wearer's body. Thus, the PDs attempted to incorporate abstracted human body features into the exterior design of the JIZAI ARMS. For example, we thought that the thickness of the robotic arms would be one of the most challenging aspects of the design. Joints in the human body are driven by the contraction of muscles that typically pass over at least one joint and are connected to the bones. Therefore, limbs are largest in volume between joints where muscles exist. Conversely, to make a robotic arm which moves like a natural human arm with electric motors, one would typically place the electric motors at the joint. This leads to the largest volume typically being around the joints. This difference can create a differential visual impression between a human arm and a robotic arm. The PDs varied the thickness of the robotic arm, even within one part, such as the forearm or upper arm, to give the appearance of similarity to the musculature of the human arm.

In order to realize a human-like appearance, the robotic arm was designed to consist of core structural members that support the weight with exterior covers that give it a curved appearance. The exterior covers provided volume to the structural member and hid the motors which drive the arm's motion. The curves of the cover were also designed to mimic the muscular arrangements of the natural human arm. The PDs specifically designed the JIZAI ARMS to reflect this feature not only when viewed from a certain position, but from various angles.

Given that it was planned for four (up to six) robotic arms to be attached to the JIZAI ARMS, the total weight of the JIZAI ARMS was expected to be heavier than previous wearable SRL systems with one or two arms. The PDs tried to minimize the volume concealed by the cover to give the appearance of having less weight while maintaining a shape similar to a natural human arm.

4.2.3 Finding Compromise in Conflict. The SA and manufacturer laid out the parts and a set of mechanisms to fulfill the functions of the JIZAI ARMS within in the exterior design specifications. CAD

Figure 8: Each member with a different physique tried on a current prototype of the base unit and identified necessary modifications. We also decided to remove the part (yellow lined in the right picture) to improve the appearance.

data for 3D models and parts layouts provided by the PDs served as the basis of the design.

When conflicts between the appearance design and the mechanical design in detail occurred during the process, the team shared the problems, discussed solutions, and changed the details of the mechanical design. The team always prioritized consistency with the concept first when making design decisions. In particular, the size of the robotic arm was to be similar to that of a natural human arm, and the exterior surfaces of the arm were to be curved to harmonize with the human body. This resulted in high demands on the size of the exterior enclosure and was an issue in several cases. For example, the manufacturer discovered that the internal components would not fit in the desired enclosure size. A simple solution would be to thicken the robotic arms. However, the SA conducted a detailed review of the size of the parts and where they could be placed. He then proposed an alternative arrangement to avoid changing the PD's exterior design. Whenever similar conflicts occurred, the SA was primarily responsible for working closely with the manufacturer and proposing alternative ideas which would minimize a change to the exterior design.

4.2.4 Refining the prototype of the JIZAI ARMS. The manufacturer proceeded to procure and manufacture parts for the JIZAI ARMS after the detailed design was approved. After some progress in assembly, the HARs, the PDs, and the SA visited the manufacturer's lab to check and discuss a work in progress version of a prototype of the JIZAI ARMS. After a discussion, several changes were made to better match the desired aesthetics for the JIZAI ARMS.

In particular, we carefully considered the appearance of the base unit. Since the base unit is placed at the boundary between the JIZAI ARMS and the wearer's body, we strived to achieve a sense of unity between the human body and the base unit. During the visit, our team members, who had a range of physical body types, took turns wearing the base unit. After seeing the base unit on several body types, the PD requested that the manufacturer put it higher than its current position. Specifically, they requested that the base unit be placed high enough that the top terminals could be in the ideal position, at the height of the wearer's shoulder blades. The PD also indicated that parts of the black fabric base of the base unit which were not under the exterior cover should be removed (Figure 8).

4.2.5 Preparing a controller for the role-playing. To provide a convenient means of controlling the JIZAI ARMS, we developed a controller which was a half scale model of the JIZAI ARMS (shown in Figure 9 Left). This controller would make it easy to experience the interaction/communication patterns and scenarios defined early in the design process. Although the JIZAI ARMS system has the extensibility to integrate with various control methods, such as those previously proposed in works like [72, 73, 75], we opted for a leader-follower control scheme for its simplicity in operation.

5 FINDINGS FROM THE ROLE-PLAYING

Below is the list of participants who took part in the role-playing sessions. While several other participants also joined the sessions, we especially focus on the listed participants in this paper as they were able to provide impressions that vividly describe the experience of wearing JIZAI ARMS.

R-1: One of the HARs who comprehensively contributed to our collaborative design work.

R-2: One of the HARs who directed this project as a project manager. (only participated on Day 1)

D-1: One of the PDs who contributed to the detailed design of the JIZAI ARMS.

D-2: One of the PDs who contributed to designing the three-fingered hands.

SA: The SA who contributed to the overall development.

VG: A videographer who was invited as a guest to promote this project.

5.1 First Impressions

Although we computationally weighed and tested the strength of every part during the manufacturing process, the first role-playing session was the first time we were able to physically sense the weight of the JIZAI ARMS. We noticed that it was possible to recognize where the robotic arms were currently attached to the wearer's base unit through changes in the center of gravity and the sense of weight. Since the base unit was carefully designed to tightly fit to the back of the body, we did not feel like the JIZAI ARMS were loose, even when wearing three or four robotic arms.

The sounds generated by the moving robotic arms were unique. As researchers who have experience using robots, we are familiar

Figure 9: Left: An operator operates a wearer's robotic arms. Right: A wearer operates the worn arm himself.

with sounds generated by computational servomotors. However, the robotic arms of the JIZAI ARMS made a creaking sound. This was caused by the 3D printed covers rubbing against each other and the sound from the gears inside the covers. For the SA, who tuned the system in the days leading up to the role-playing sessions, these sounds were not a surprise. For the other members, who first encountered the arms at the role-playing session, however, it was deeply moving as it sounded organic and gave the impression that it was a living thing.

Since we conducted the first role-playing session in a dance studio with mirrored walls, we were able to clearly see how our body image was changed when wearing the moving JIZAI ARMS. However, without seeing the mirror, we noticed that one felt as if a human arm (not their own) was coming at them when seeing a robotic forearm. This contrasted with our previous experience working with SRLs in which we thought an inorganic robotic object was approaching. We also felt fear when a robotic arm closely approached our face. Overall, it was a strange experience wherein we rationally understood that our body shape and movements were altered by the JIZAI ARMS when looking in the mirror, but observing the JIZAI ARMS directly induced a strong sense of fear due to not understanding where the arm was coming from.

We noticed that where the robotic arms were attached could vary the impression given to the wearer. R-1 described, *"the white wings reminded me of characters wearing wings described in movies, animations, and picture books, and makes the wearer look as if he is about to fly! At the same time, the wearer's shoulders look as if they are very square, giving the wearer the appearance of being strong."* VG also gave us her impression, *"when the wearer received two arms on the top terminals and the arms are visible from the wearer's front, they suddenly look like a kind of character."* D-1 mentioned, *"I used to dance and often checked my own body movements while looking in the mirror. I explored physical expressions and tried out various body movements. Perhaps because of this, I did not carefully observe the robotic arms moving near me."* D-2 commented on the gap between his own impressions and when he saw the videos recording him wearing the JIZAI ARMS, *"when I was wearing it, I subjectively felt I was large, but I was surprisingly puny in the video! Especially when I was wearing two on top, I felt stronger because my shoulders were enhanced, but it was not so in fact."* In the first role-play session, we virtually simulated how a wearer fits the JIZAI ARMS and were able to explore the impressions, varying due to the attachment positions. We were able to see how real humans of different looks and physiques wear the JIZAI ARMS and learned from various impressions of digital cyborgs empowered by the JIZAI ARMS.

5.2 Operation by Oneself or by Another

Whether the JIZAI ARMS are being operated by the wearer, oneself, or other(s) gives a completely different impressions to the wearer(s,) as shown in Figures 9 and 13. At the beginning of the role-playing session, each participant experienced the JIZAI ARMS only with one robotic arm remotely operated using the controller (Figure 9 Left), and after that, he/she tried to operate the arm by him/herself (Figure 9 Right). D-1 expressed that, *"I became more aware that it was my own body when I operated my worn arm, and got an impression that the operation of the controller also became transparent, as if it had become a part of my body."* On the other hand, R-1 noticed that, when the non-wearer is operating the controller and the robot's hand comes close to the wearer's face, the wearer would avoid it, but not when he/she is controlling it by him/herself. We expect this is because the movements are unpredictable and the wearer is fearful when an arm is not under their control. As a different perspective, the SA described when D-2 operated the controller and grasped the SA's hand using his own a robotic limbs, *"I feel like I'm being pulled by the hand of a small child even though I am alone."* On the other hand, D-2 mentioned, *"I felt like I could move the arms with the controller more fully when I was manipulating someone else's robotic arms."* The difference in the impressions of the arm's performance between self and other's operation was observed in both participants seeing themselves in the mirror or directly.

There were cases in which we needed to operate multiple arms at the same time. We received some impressions regarding both when the wearer themselves operated the arms and when the arms were operated by others. When operating multiple robotic arms, at least the same number of "real" arms were required. Ideally the same number of operators are required to accurately and safely operate all of the robotic arms. How to operate multiple robotic limbs at the same time is a research issue in the SRL research [72, 73, 75]. As of writing, there is no perfect way of controlling multiple arms simultaneously. In this role playing, we sometimes observed three

Figure 10: Three operators shared the controller and manipulated three arms respectively.

Figure 11: A person is detaching a robotic arm from a terminal of a wearer's base unit.

operators controlling an arm each for a wearer with three robotic arms, which weird moments, as shown in Figure 10.

5.3 Attachment/Detachment

The experience of attachment and detachment left us with a strong impression. We noticed a particular feeling when the wearer attached/detached a robotic arm to/from a terminal on his/her back. Detachment (Figure 11) made an especially strong impact on the wearer. The combined sense of vibration, sound, and force when an arm connected/disconnected to/from a terminal was entirely different from the feeling of the robotic arm(s) moving when fixed to the base unit, even though it is impossible to measure the differences between these senses. R-1's impression was a follows: *"I didn't feel much of anything after it was attached, just a little heavier. But I felt more of a sense of loss after it was detached."* R-2 agreed with this opinion, and left his own impression: *"when the arm is detached, the sound and vibration of the detachment, the sudden feeling of lightness in my body, and the actual appearance of the detached arm in front of my eyes. When I held it up, I was surprised at its weight. I felt that the weight of the detached robotic arm was heavier than when it was working in unison with my body. This experience is similar to when I was playing the guitar and suddenly the strap came off and quickly had to grab the guitar's neck."* D-1 expressed, *"there was a sense of being 'pulled out,' since my body felt resistance when it was removed. However, when the SA (who was most experienced with maintaining and operating this function) did it, I felt little resistance and felt it was like 'when a tooth is removed'."* R-2 described the feeling of a rough detachment to be as if an inexperienced nurse had to go through the trouble of drawing blood, sticking the needle in several places and finally finishing the blood draw.

The experiences described above were provided by the planned functions that we defined early in our design process. However, interestingly, we interpreted that there was a breakdown happening and a puzzled feeling caused by the detachment in particular. However, we encountered real breakdowns on the first day of role-playing, and describe the impressions of them next.

Figure 12: The broken arm was wrapped with black tape.

5.4 Encountering a Breakdown

On day 1, we identified an anomaly in one of the arms when checking them. At that time, R-2 was operating the controller, and we noticed a strange noise from the arm. Eventually, we found that there was a small problem with an integrated mechanical part inside the body, so we decided not to use it and to fix it at a later date. As we mentioned, when the JIZAI ARMS move they make a unique sound. But R-2 who operated this broken arm was not able to identify the difference between the sound of it working correctly working or it being broken. As a result, he initially interpreted that there was a problem with his operation. As such, the arm breaking was a kind of traumatic experience. The SA tightly wrapped the broken arm with black tape so as to not move the problematic part as shown in Figure 12. Though this emergency measure was just for temporary maintenance, it gave the other participants a strong and memorable impression. Interestingly, we encountered unique impressions from both the attachment/detachment function we intentionally designed and an accidental and unexpected breakdown on the same day. While the SA relatively easily identified the breakdown, the others were unable to differentiate between a planned experience and a breakdown, which left them with a strong impression. Though we faced the breakdown on day 1, after reflecting on the experience and finding problems, we successfully

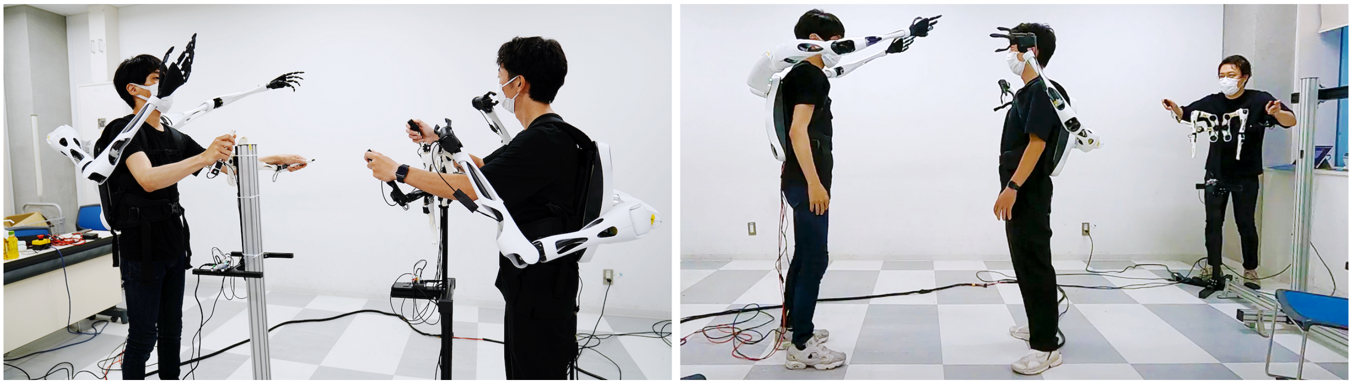

Figure 13: Left: Operation of the arms by the wearers themselves, Right: Operation of the wearers' robotic arms by non-wearers

repaired the whole system and conducted the day-2 role-playing without any errors.

5.5 Sense of Number of Worn Arms Changing

On the second day of role-playing, some participants became so accustomed to wearing the JIZAI ARMS that they could precisely sense the number of arms they were wearing and their positions. This may have been caused by the fact that we did not prepare a mirror on this day, to let the participants concentrate to their own senses. D-2 described his sense of balance when removing the arms, *"It was interesting to feel the sudden change in balance and I wobbled when the arms were removed. Especially when the number of arms changed from one to zero, I didn't really expect it."* R-1 also mentioned, *"When I wore the fourth one, I felt strange because it was symmetrical but felt heavy on the right side, so I moved my body to check my sense of balance."* On the sense of wearing four robotic arms, D-1 said, *"Compared to the feeling when the number of arms was 'decreasing,' I didn't feel a big change although feeling my body was heavier when 'increasing.' Yet, when I moved the worn arms and put them in front of my body to see them, and when I moved them myself to confirm that they were tracking, I eventually realized that I had four arms now."* On the other hand, D-2 explained his feeling when he was an operator manipulating D-1's arms and D-1 removed one arm from two, *"I used to move the two manipulators while balancing it on both sides (like riding a bicycle), but now that I have only one hand, I find it hard to do it and end up moving both hands."* Interestingly, we experienced a stronger impact when reducing the number of arms worn than when increasing. However, we have not evaluated this phenomenon through an empirical survey yet.

5.6 Wearing Arms Another Person Used to Wear

In addition to our impressions of when we experienced reducing the number of arms worn as above, there was subjective feedback on when receiving arm(s) from another person. R-1 described when she received two arms from the SA and wore four arms (Figure 14), *"Rather than being happy to have more arms, I felt pushed to do so. It was like when I lost at rock-paper-scissors and was forced to carry everyone else's school bags when I was a primary school student!"* For an opinion from the side receiving more arms, D-1 said, *"I felt like I had the upper hand when my opponent's arms were reduced."* As such, the experience of receiving extra arms from another person and additionally wearing them is different from when just wearing many robotic arms.

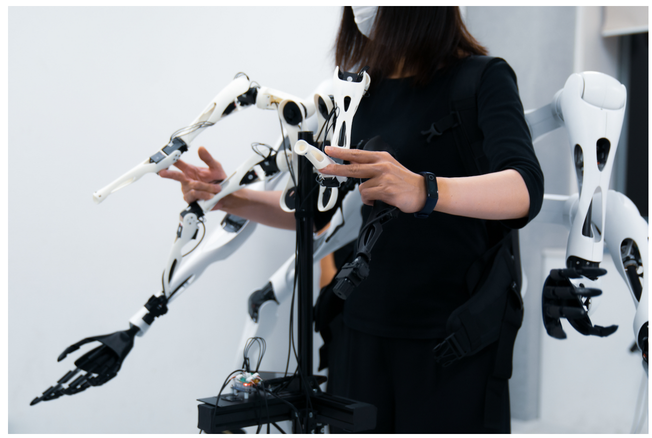

Figure 14: R-1 is struggling to operate four arms after receiving two from the SA.

5.7 Giving/Receiving Arms, My Arm or Your Arm?

Herein, we describe our findings on whether the JIZAI ARMS can induce the feeling of being given an arm without a transferal of ownership. Namely, being given an arm which was formerly worn by another person and the recipient feeling as if the arm was of the former wearer and not the recipient. D-1 described, *"When receiving an arm from D-2, I did not feel it was his arm. But, after manipulating it myself, I felt it was mine. I thought that I did not spend enough time living with the arms, and had not accepted them as mine. This is similar to when I begin to use a new tool."* D-2 described, *"this experience is a little bit similar to lending a guitar to someone but not the same yet."* R-1 shared her impression: *"At a baseball game, JIZAI ARMS gives me the feeling of batting with another person's bat when I was in a slump and wanted to be like the person who hit a lot recently! If an arm had a little more character, like it would be lighter, heavier, or a little more expensive."* On the first day, R-2 removed his Apple watch from his left wrist and put it on a robotic arm's wrist to feel ownership of the arm. It seems there is room for the JIZAI ARMS to be more personalized. As an objective opinion, the VG gave us her impression, *"I realized that it is still difficult to feel a sense of ownership even with the JIZAI ARMS, which is the same as when I experienced a SRL system before. I wondered what is necessary to have a sense of ownership, such as 1) generating some kind of feedback of the arm movement somewhere in my body, 2) if I become more dexterous in what I can do with my arms and hands, maybe it will be easier to use and easier to get into, 3) eliminating my arms."* We cannot strongly argue how one adopts the JIZAI ARMS as a part of their body through the limited findings we were able to gather from the two days in which we played with the JIZAI ARMS. But we noticed that we can interpret each separated arm as being similar to tools on the human body scale, like a guitar or a bat, that becomes more comfortable to use with one's body and gives a sense of ownership over time.

When the SA and R-1 collaboratively experienced the JIZAI ARMS with manipulators, D-2 for the SA and D-1 for R-1, we came up with a task for them to do. They passed a small stuffed toy to each other using their robotic arms, as shown in Figure 15. R-1 described the moment as, *"when D-1 manipulated one of my robotic arms and handed over the toy to R-1, even though I was distracted by my phone, I was surprised and found it convenient that my additional arms did the work for me!"* We observed in this interaction that the SA deftly bent his knees to assist the robotic arms to successfully pass the toy. The SA explained his performance: *"since we were the first to perform such a collaborative task with each other, I was thinking that I should just move sideways. I avoided multiple arms overlapping because the arm's range of motion would be limited if I used my upper body to align the arms. I was doing the set of motions while thinking about how I could move according to the arm's will."* As an expert on operating the JIZAI ARMS, the SA has completely mastered how they work, including the quirks, so he successfully assisted in this collaborative task.

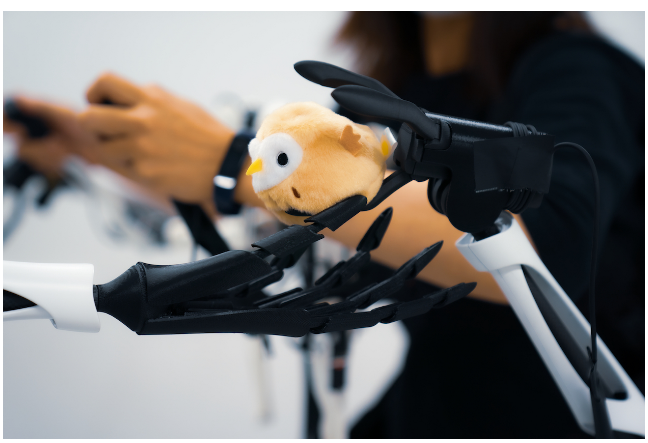

Figure 15: R-1 is trying to pass a small stuffed toy to the SA.

6 DISCUSSION

6.1 Sense of Body Ownership towards a Robotic Body Part

The findings we gathered through designing the JIZAI ARMS provide several insights for those involved in future projects seeking to produce digital cyborgs and researchers investigating how humans adopt digital cyborgs or human-machine integrated technologies into their everyday lives. One major area of interest to persons involved in adjacent fields is how to produce a situation in which a human could achieve "a sense of body ownership" towards a robotic body part, as prior works have suggested is possible [2, 5, 16, 23, 57, 78]. From our first-hand study using the JIZAI ARMS, we made several findings relevant to this area of interest with implications for future research issues.

Through our experiences, we were able to reveal that one could sense how a worn robotic limb moves when worn, as well as its position on the base unit when tightly held on the back. This is despite not preparing any methods of explicit feedback (such as multi-modal stimulations [5]) to induce a sense of body ownership towards the artificial body part. Our findings, on the other hand, support a previous research result [15] that found, when experimenting with actual robots, additional tactile stimulation may not be necessary to understand the state of the robot (a key component of body ownership) since there are various physical stimuli from the device itself.

When losing or taking off a robotic arm, we noticed that the wearer needed to be aware of the change of body balance (as also pointed out in a previous work [25]). In sports science research, there is a report which notes that short distance runners with unilateral forearm amputation can wear prosthetic arms to keep their balance and run well [27]. However, in contrast, several participants in our study suggested that humans could adapt to wearing robotic arm(s), rewriting their body balance image, and found it strange when an arm was removed, despite returning to a state with symmetry, in which they were wearing no additional robotic arm. If the fundamental mechanisms of such somatic senses can be elucidated, the JIZAI ARMS can be used in future research exploring and pushing the boundaries of an established understanding.

The sense of loss is one of the critical issues in implementing digital cyborgs into everyday lives, as argued by Kieliba et al. [36] in their experiment when obtaining and losing an extra robotic finger, though this area has not yet been sufficiently explored. In our study, the sense of loss was induced when one lost a robotic arm. This gave one the feeling of a breakdown happening and a sudden feeling that the worn robotic arm was a part of his/her body. After experiencing this loss, we may be able to hold a separated arm and feel its weight, but it will be dissociated from oneself and thus have a qualitatively different feeling of weight and touch when compared with when it was worn or attached/detached. This can be explained by Heidegger's breakdown theory of embodied tools, which has been also discussed by Winograd [86] and applied to HCI design. In fact, we noticed that the JIZAI ARMS provide a strong sense of loss to the wearer when removed. Even from the small sample size in our study, we would like to suggest that there is great importance in designing the sense of loss to induce a sense of ownership towards an artificial body part in future human augmentation design projects.

As an implication for future research, we would like to emphasize the need to carefully consider the aesthetics of the product when realizing digital cyborgs. While it is known that the appearance or form of additional body parts is relevant to generating a sense of body ownership towards them [74], a recent article [2] suggests that humans may embody inorganic-looking robotic limbs with a sense of ownership as well. As of now, we hesitate to argue if the aesthetics of our JIZAI ARMS contribute to generating a sense of body ownership in the wearers since only we subjectively experienced the prototype. However, we are eager to figure out the relevance of aesthetics and the sense of body ownership in our future research.

6.2 Social Ownership in Digital Cyborgs

Beyond the topic of designing one person's subjective experience as a digital cyborg, we are eager to discuss how to consider social interactions between multiple digital cyborgs existing together, especially how digital cyborg A might identify an artificially made body part as his/hers and how digital cyborg B might also recognize it as cyborg A's. Unfortunately, while multiple participants stated that they could feel ownership of the JIZAI ARMS they wore, they did not feel a sense of *ownership over another person's body part* despite exchanging arms at times.

However, through trying a set of social interactions, we came up with future research issues to investigate this *social ownership*. As we liken the existence of a robotic arm to a guitar (R-2 and D-2) or a baseball bat (R-1)—human-scale tools a user lives with longer-term and constructs a feeling of ownership over, long-term acceptance [28, 29, 58, 70] of the JIZAI ARMS should be a future research topic to investigate social ownership for digital cyborgs. We also suggest adding customizability to an artificially made body part. Referring to recent studies on personalizing humanoid robots [43], speaking AI agents [47], and other similar works, we speculate on an approach to preparing a robotic body part's unique haptics, vibration, sound effects, even decorations. These data could be uploaded to the cloud and be transferred to whatever arm the user was wearing. Future research may investigate the relative contribution of the settings and hardware towards the sense of ownership.

Another direction is a concept of the universal body part. Similar to a bicycle sharing service—where many identical bicycles are equally maintained at the stand, and when a user rides, he/she feels this is his/her own bicycle; robotic arms with identical designs, like the JIZAI ARMS, could be used by everybody as a universal body part through a sharing platform.

As for long-term research, studying how one (e.g., dancers, comedians, and other physical expressionists) continuously uses the JIZAI ARMS, completely adopts it, and performs as a digital cyborg will reveal a soma-aesthetic [28, 29] experience in post-phenomenological internal understandings [69]. For scientists investigating augmented humans (e.g., [2, 30, 81]), a study on the long-term use of the JIZAI ARMS may provide interesting insight into how the body image in the brain shifts through the experience of becoming a social digital cyborg.

6.3 Methodology for Producing a Digital Cyborg

In our design process, we refined the JIZAI ARMS following the tradition of product design with multiple body-storming sessions, and yielded a design which can be used by anybody to become a digital cyborg. However, in contrast, there is an alternative direction in human augmentation research seeking to produce realistic human-like body parts, such as a series of Android robots produced by Hiroshi Ishiguro [31] and art works by Stelarc [76]. This realistic direction seeks to artificially copy a particular human's body part(s) which are meant to be used by that human being.

By illustrating our process in as much detail as possible, we have tried to convey a design direction for designing a system that allows anyone to become a digital cyborg and can be widely accepted in people's everyday lives. There are several related research topics such as considering how to co-exist with robotic agents [82, 85] and transhumanism in extended reality (XR) situations [66]. Indeed, some researchers have begun to discuss methods for human-machine integration or digital cyborgs [11, 30] and design for particular objects, e.g., a hearing aid [35] and an e-bike [1]. Our interdisciplinary design and development approach documented in this paper details how researchers, designers, and engineers came together to co-create a digital cyborg system which synthesizes mechanical artifacts with the natural human body to create an aesthetically pleasing whole. This work can be referred to by future projects investigating the human augmentation paradigm and seeking to produce digital cyborgs.

7 CONCLUSION

This paper introduced JIZAI ARMS, a supernumerary robotic arm system consisting of a wearable base unit and modular arms that can be attached, detached, and exchanged between multiple wearers. Referring to recent research in human augmentation and producing digital cyborgs, we sought to speculate on a vision of the future in which multiple digital cyborgs (humans wearing the JIZAI ARMS in our case) interact, give, and share their robotic body part(s), by designing and manufacturing the JIZAI ARMS and physically experiencing a prototype ourselves. From our role-playing sessions, we found that our bodies could precisely sense the attachment/detachment of arms, and we especially felt a strong impact when detaching or reducing the number of robotic arms worn. We also suggested adding customizability to the robotic arms to generate a sense of social ownership, an individual's sense of ownership towards a specific artificial body part shared among multiple persons, as a future research topic. We believe that our autobiographical research account will contribute to future projects aiming to design digital cyborgs and human-machine integrated approaches in general.

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A TECHNICAL SPECIFICATION OF JIZAI ARMS

As an appendix, we note technical specifications of the JIZAI ARMS system developed in our design process and used in the role-playing sessions. Figure 16 (a) shows the appearance of the JIZAI ARMS. The JIZAI ARMS consist of a base unit worn on a body of a wearer, and robotic arms, which can be smoothly attached to and detached from the base unit without the use of tools. The hand module of the robotic arm is designed to be interchangeable depending on the task at hand. This set in Figure 16 (a), one base unit and four robotic arms, weighs approximately 14kg.

A.1 Base Unit

The base unit (Figure 16 (b)) is the interface connecting the wearer and the robotic arms. The wearer can wear the base unit as if they were carrying a backpack. Shoulder straps, a chest strap, and a waist strap are used to keep the base unit and the wearer's back in close contact. The shoulder straps, waist strap, and the surface of the base unit facing the back of the wearer are cushioned to alleviate the strain of wearing the JIZAI ARMS.

The base unit has six terminals to which robotic arms can be attached. Two terminals are located at the top, middle, and bottom of the base unit, respectively. The terminals are not located on the same plane to minimize collision/contact among the robotic arms when power is not applied to them. The connecting surface of the top and bottom terminals are tilted 15 degrees upward/downward and outward, respectively.

Each terminal has an electrical connector at its center and contains an encoder to sense the angle at which the robotic arm is attached. The robotic arm can be fixed to the terminal at any angle in 5-degree increments. Both mechanical and electrical connections can be completed by just mounting the robotic arm. The weight of the base unit is 4.1kg.

A.2 Robotic Arm

Only one type of robotic arm was developed. However, any arm with the appropriate terminal specification could be connected to the base unit. The robotic arm developed in the scope of this paper consists of three limb parts, a scapula, an upper arm, and a forearm. A hand module can be installed on the distal end of the forearm by using a hex wrench. The kind of hand that is attached can be changed flexibly.

The lengths of the robotic arms were determined such that, when extended, they would be in front of the wearer's body, and about the same length as the wearer's natural arms [53]. The dimensions of the robotic arms are shown in Figure 17 Left. The robotic arm has five active joints (See, Figure 17 Right). Geared servo motors (XM540-W270-R/XM430-W350-R (elbow yaw only), ROBOTIS INC) drive each joint of the robotic arm. The two proximal joints, shoulder pitch and shoulder roll, have extra gears outside of the servo motor such that sufficient torque can be provided. The reduction ratio of both joints is 2:1.

A.3 Hand Module

We prepared two kinds of interchangeable hands, one is a three-fingered manipulator for conducting picking/holding tasks, and the second is a 3d-printed five-fingered hand for use in creative bodily expressions. The three-fingered hand has a small geared servo motor (XC330-T181-T, ROBOTIS INC) to open and close the three fingers connected to a ball screw. The distal end of the robotic arm's forearm and the three-fingered hand are connected by a passive joint. The central axis of the hand's three finger is connected at a 45 degree angle to the long axis direction of the forearm. A screw with silicon washers connects the three-fingered hand to the distal end of the robotic forearm. The angle of the passive joint can be changed by placing the tip of the hand against an object. The five-fingered hand is fixed to the distal end of the robotic forearm using a screw.

A.4 System and Control Architecture

The JIZAI ARMS can be controlled through a PC application made in Unity (Unity Technologies). The PC application works on a laptop PC (Surface Pro 8, Microsoft Corp.) with Windows OS (Windows 11 Pro, Microsoft Corp.). A power cable from an external power source and a USB cable from the laptop PC can be connected to custom made circuits in the base unit through a small slit at the bottom of the base unit.

The one USB port of the laptop PC is connected to a 1:4 USB-hub in the base unit. From the USB-hub, two USB cables connect to the custom circuit board installed in the base unit to control the JIZAI ARMS. The USB signals from the USB-hub are each routed to a USB Hi-Speed four-port bridge chip (FT4232H-56Q, Future Technology Devices International Limited) on the customized board and are

Figure 16: Appearance of the JIZAI ARMS. (a) The JIZAI ARMS being worn. (b) The base unit with six terminals for mounting the robotic arms. (c) A robotic arm with a three-fingered hand. (d) A terminal on the base unit. Magnified view inside of the dotted line of (b).

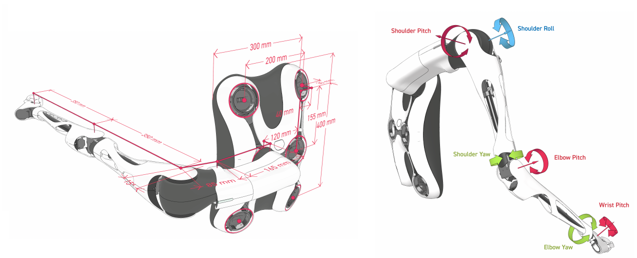

Figure 17: Dimensions (Left) and joint arrangement (Right) of the JIZAI ARMS.

Figure 18: Hand modules. Left is the three-fingered manipulator. Right is the five-fingered hand.

converted and extended to four serial UART signals (for a total of eight). Each UART signal is converted to meet the RS-485 standard on a customized board and are wired to the electrical connector at the center of each terminal of the base unit along with a 12V power line (a total of six, two of the UART signals are unused). In each robotic arm, five motors are daisy-chained via a RS-485 multidrop bus. After attaching the robotic arm to the terminal of the base unit, all geared motors of the robotic arm are powered and can communicate with the laptop PC through one virtual COM port. From the laptop PC, each robotic arm appears as its own virtual COM port, and up to six robotic arms can be controlled from six virtual ports of the laptop PC.

A.5 Controller to Manipulate Multiple Arms

The overall structure of the controller was created by modifying 3D CAD data of the full-size JIZAI ARMS. Its body was produced in-house using a 3D printer and assembled by the PDs and HARs. Each joint of the controller contains a small geared motor (XC330-T181-T, ROBOTIS INC) with an integrated encoder to obtain the joint angle. All motors in the controller are accessible through one COM port on a controller PC via a USB-Serial interface board (U2D2, ROBOTIS INC). A half duplex asynchronous serial communication scheme disclosed by the manufacturer of the motor is used to communicate with the motors. The maximum communication speed was 1M bits per second.