xLimb: Wearable Robot Arm with Storable and Extendable Mechanisms

Zeyu Ding, Shogo Yoshida, Takuma Torii, Haoran Xie
Japan Advanced Institute of Science and Technology
Ishikawa, Japan
xie@jaist.ac.jp

ABSTRACT

To develop a wearable robot arm that can support our daily activities, we aim to propose a novel wearable device, xLimb, that can feature multiple functions of both storability and extendibility without obstruction to wearers. The proposed device will be mounted on the upper arm to ensure that the center of mass of the device will remain close to the wearer, whereby the exerted burden on the wearer and the servomotor can be decreased. Meanwhile, the folding state provided by the storable mechanism enables the proposed device to maintain a compact size, to avoid hindering the wearer's main activities when not in use. We developed a prototype of our xLimb to verify the proposed mechanisms and conducted a user study with different usage scenarios for participants to experience. The evaluation results indicate that the proposed device can improve user experience as a wearable robot arm.

CCS CONCEPTS

• **Human-centered computing** → **Interaction devices**; **Accessibility design and evaluation methods**.

KEYWORDS

wearable robot arm, human augmentation, physical augmentation, extendable mechanism.

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1 INTRODUCTION

Human augmentation is an emerging research field that has been explored intensively in the past decade. Physical augmentation of the human body is an important topic in human augmentation; it has a long history of practice. Since ancient times, artificial limbs have been developed for disabled people to help them maintain their daily activities with simple functions such as drag and push. Benefiting from the rapid progress of manufacturing, robotics, and other related technology, human augmentation has become more feasible to provide the user with augmented functions through wearable devices and sensors.

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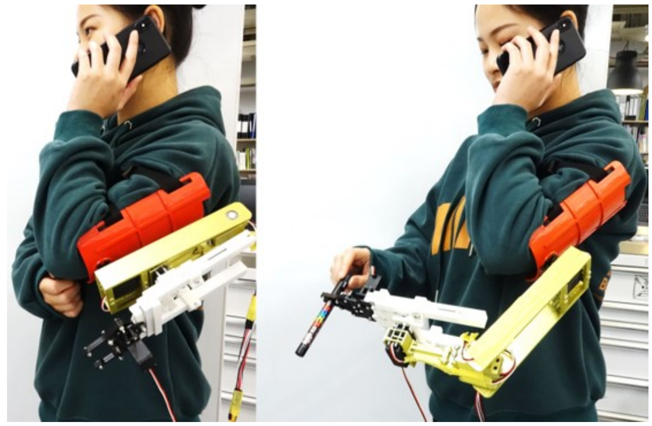

Figure 1: xLimb mounted on a wearer's upper arm in compact folding (left) and unfolding states (right)

In this work, we focus on the wearable robot arm as a typical and prominent wearable device. Since the arm is considered one of the most important organs in human beings, many studies have been conducted on augmenting the ability of upper limbs. The wearable robot arm can be utilized as a third arm to help a user in a working scenario [1] and as a user interface for programmable control [2]. However, most existing wearable robot arms are not user-friendly enough. The two main drawbacks are the hindrance to a user's main activities and limited reachable range. If the wearable device is not being used, the device may occupy significant space and cause hindrance to the user's activities or other people around the user. Previous works adopted multi-joint artificial limbs with fixed lengths, whereby the reachable range was limited in the device design. In our pilot study, we found that a larger reachable range is preferred for daily support tasks.

To solve these issues, we aim to propose *xLimb* - a wearable robot arm device with both storable and extendable mechanisms, as shown in Figure 1. It was inspired by the natural wing functions of ladybugs. Its hard outer wings are used to protect itself, whereas its soft inner wings are used for flying, and can be folded up under the outer wings while not being used. Similarly, we considered the storability function to enable the device to move freely when in use and store onto the body when not in use. For the extendable mechanism, we were inspired by the jaw structure of the goblin shark. When hunting for food, the shark extends its jaw to fetch distant prey at a high protrusion speed. Therefore, we adopted a scissor unit for the extendable mechanism [3]. We constructed a prototype of xLimb (Figure 1) and conducted a user study to verify the effectiveness and user experience of the proposed device.

The main contribution of this work is to propose a novel wearable robot arm with storable and extendable mechanisms for human augmentation and to evaluate its use in various scenarios.

2 RELATED WORK

Physical augmentation, as a subfield of human augmentation, aims to repair or enhance the functionality of human body parts, and add extra body parts to gain extra abilities. This research topic is also related to the fields of wearable computing and human computer interaction. In this regard, a wearable multi-joint device was proposed to enhance the human capabilities on the wrist [2]. A bionic tail-type was proposed to endow humans with extra abilities of weight support and emotional expression [4]. Egospace proposed a wearable device to guide the wearer with the projection information [5]. The augmented clothes were proposed to augment the human thermal sensation with retractable structures [6]. In this work, we focus on wearable robot arms that can support the wearer as a third arm in daily activities.

There are numerous works on wearable robot arms in both the robotic and human computer interaction fields. Naito et al. proposed a wearable robot arm to assist with overhead work that requires large muscular power, such as carpentry [7]. A supernumerary robotic limb, mounted on the shoulder and upper body, was proposed to eliminate fatigue and injuries to workers [8]. To improve user-friendliness of wearable robot arms, optimization of the device structure was proposed to decrease the arm's weight [9]. Drohne et al provided an experimental evaluation method including attachment position and other attributes [10]. MetaLimbs utilized legs motion to control the robot arms mounted on a user's back [1]. For these proposed devices, the wearable robot arms are usually quite large and inconvenient while not in use. Therefore, we aim to improve the user-friendliness of a wearable robot arm by embedding storable and extendable mechanisms.

3 XLIMB: THE PROPOSED DEVICE

To achieve the desired wearable robot arm, we first conducted a pilot study of the ideal image from the common users' perspective. We then developed a prototype with the proposed mechanisms.

3.1 Pilot Study: Survey on Ideal Robot Arms

In our pilot study, we aim to find the ideal images of a wearable robot arm. We confirmed the investigation items with fourteen graduate students through a questionnaire featuring the following questions about the ideal wearable robot arm: 1) the most conceivable scene to use; 2) the important features; 3) the ideal body part for wearing; 4) the ideal length. By analyzing the results of the questionnaire, we determined that an ideal wearable robot arm may be described as follows: 2.

(1) The most conceivable application scenarios are "enhance the wearer's capability in manual labor" and "interact with objects instead of their own hands (such as lifting a hot coffee cup)".
(2) Storability and extendibility are important features for a wearable robot arm. Storability is considered a more important property than extendibility.

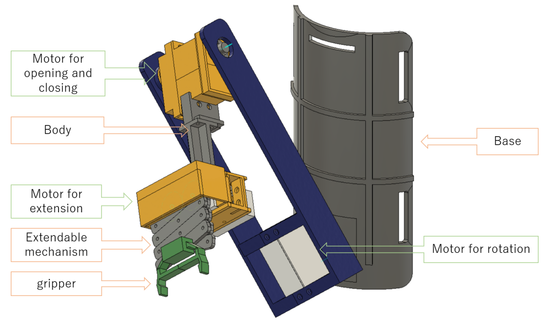

Figure 2: System configuration of xLimb

(3) Most subjects thought that comfort and operability are significant for a wearable robot arm.
(4) More than half of the subjects thought that the forearm is an ideal body part to mount a wearable robot arm.
(5) For most subjects, an ideal reachable length of a wearable robot arm is 1.0-1.5 times the distance from elbow to fingertip.

We found that there were inconsistencies between questionnaire responses. For example, for those participants who had selected the forearm as an ideal body part to wear a wearable robot arm, most of them also selected "enhance the user's capability in manual labor" as a conceivable application scenario. However, the forearm may not be an ideal choice because this may cause a heavier burden than wearing the robot arm on the wrist or shoulder. In other words, we think a wearable robot arm on the forearm is not the best choice for manual labor because these inconsistencies happened due to the loss of the real usage experience of a wearable arm from subjects.

After eliminating the inconsistent answers, we determined that the ideal image of a wearable robot arm for daily activities is as follows:

(1) The robot arm should be able to lift objects of 500g in daily life
(2) The reachable length should be 1.0-1.5 times the distance from elbow to fingertip
(3) Comfort while wearing the arm is an important factor.

Based on these features, we propose the xLimb, the lightweight and comfortable wearable robot arm for potential interactive designs.

3.2 Prototype Design

To achieve the ideal features of a wearable robot arm, we propose xLimb with storable and extendable mechanisms. Figure 2 shows the system configuration of our proposed device. The proposed system consists of an arm base, an arm body, an extendable mechanism, a gripper, and a motion controller. The proposed device has three degrees of freedom, and three types of movements – rotation, expansion/contraction, and open/closure. An application of the proposed device is presented in Figure 1, demonstrating how the wearer can use the device for support while working.

Figure 3 shows the developed prototype of our proposed wearable robot arm. The size of the prototype is 235×72×60 mm when folded without an arm base. The maximum stretchable length is about 550 mm when unfolded from the pivot of the rotation motor to the forefront of the gripper. This distance is approximately equal to the length of an adult's forearm. The net weight of the developed prototype is 678 g, which is lighter than existing wearable robot arms [1, 3, 8]. In our prototype design, we adopted three servo motors for robot control: LD-20MG motor (20 kg/cm torque) as the gripper motor for opening and closing the gripper; DS3235 motor (35 kg/cm torque) for rotation; LD-3015MG motor (17 kg/cm torque) for expansion and contraction. We used LeArm (Lobot Robot) for the gripper. The main parts of the gripper are made of metal, and the net weight of the gripper and the driving motor is 116 g. The maximum opening width of this gripper is 57 mm. The maximum weight of an object that can be grabbed by the gripper is 500 g.

We used the Fusion 360 to create a 3D model of the prototype design and printed it out using the Prusa I3 MK3S 3D printer. The filament material is polylactic acid (PLA). 3D printing time was around 24 hours. We used two belts to fix the device to the wearer's upper arm.

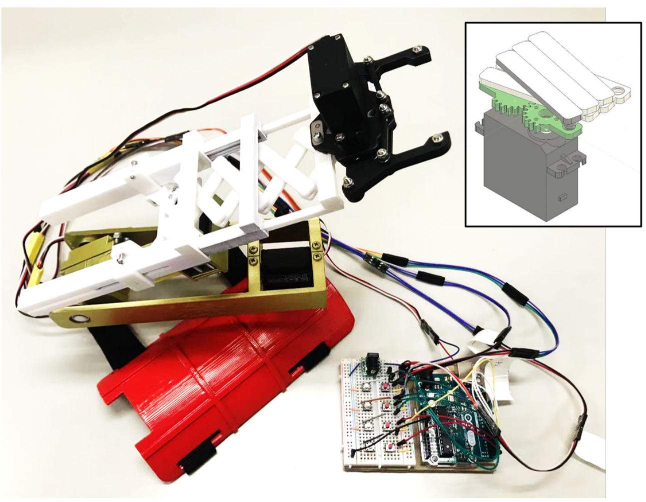

Figure 3: An overview of the proposed device

3.3 Extendable Mechanism

The details of the extendable mechanism are shown in Figure 3 (white color). The pivots and bearings of the structure were made from stainless steel to ensure bending strength. The remaining parts were all made from PLA plastic filaments using 3D printing. The distance between the two gears of the structure is constrainted by using a piece of supporter to fix pivots of the two gears to the motor. Therefore, we can control the extendable mechanism to expand or contract by driving the gear on one side. As the extendable mechanism expands, the force arm also gets longer. As a result, the force increases causing a noticeable deflection and increasing the risk of failure. To solve this issue, we added a supporter to the extendable mechanism from the outside. This drawer-like supporter can move simultaneously with the extendable mechanism, thus significantly increasing its bending strength.

4 USER STUDY

To evaluate the performance of the proposed xLimb device, we conducted a user study with the prototype. The evaluation process included an experiment while wearing the prototype and a questionnaire. We recruited fourteen graduate students (seven males and seven females, 20 to 35 years old).

4.1 Wearing Experience

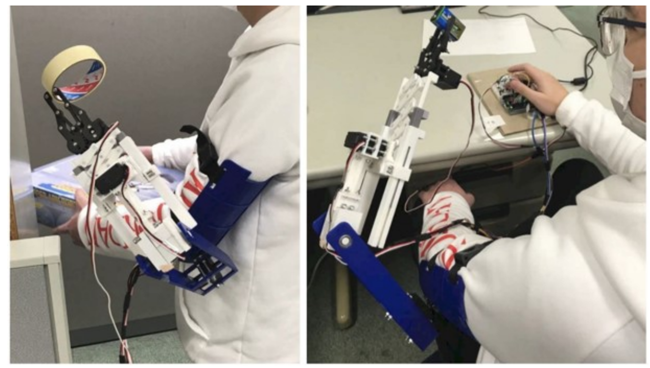

Figure 4: The usage of xLimb device in user study

To evaluate the experience of wearing the prototype, we designed three different scenarios for all participants wearing the proposed robot arm. The participants were asked to use the device to achieve simple tasks as shown in Figure 4. The application scenarios were designed as follows:

- Participants learning how to freely control the prototype by themselves.
- Using the prototype to move small objects such as battery or tape while both hands are closed.
- Achieving certain goals with the prototype in folding and unfolding states, respectively.

In the first scenario, we explained to the participants how to control the device, since the purpose of the study is to enable participants to explore the device functions by themselves. In the second scenario, the participants experience how to use the developed wearable robot arm to achieve multiple tasks using the extendable mechanism. In the third scenario, the participants perform certain tasks using the storable mechanism, such as going through a narrow aisle while carrying a box. After that, the participants experience the difference of wearing the proposed prototype in folding and unfolding states.

4.2 Participant Questionnaire

To evaluate the user experience of the proposed device, we conducted a post-experience questionnaire with all participants. We could then analyze and evaluate the system performance of the prototype in extendibility, storability, and user experience.

We provided the participants with different scenarios for device usage. The question items in the questionnaire were designed as follows (see Figure 5): Do you think the device is comfortable when wearing, inconvenient in the folding/unfolding state? Do you think storability and extendibility of the device are useful/adequate? All questions were scored on a five-point Likert scale (1 for strongly disagree, 5 for strongly agree).

5 RESULTS

5.1 Evaluation Results

The evaluation results of our user study are shown in Figure 5. The average scores of storability and extendibility questions were 4.10, 3.80, 3.86, and 3.71, respectively. In contrast with the unfolding state, the user experience of use convenience in the folding state increased by 21.3% to 3.21. Thus, the main design goals of the ideal wearable robot arm were achieved with the xLimb.

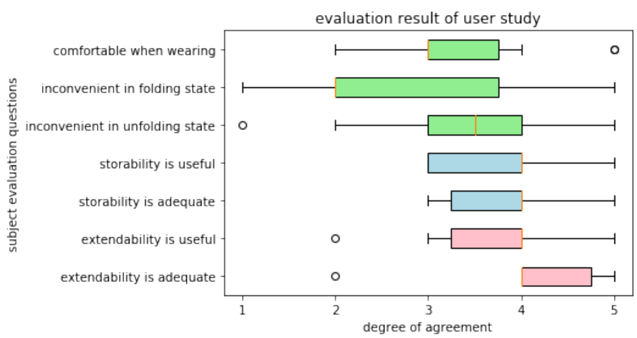

Figure 5: The questionnaire results in the user study

5.2 User Feedback

Based on the free comments from participants, we received three main types of user feedback as detailed below.

First, it is necessary to enhance the bending strength of the extendable mechanism. As alternatives to the extendibility mechanism, we decided to adopt the scissor unit mechanism because of the high stretch ratio. The stretch ratio is defined as the proportion of the expandable length to the length of the extendable mechanism. However, the disadvantage of this mechanism is a low payload. To solve this issue, we may alter the 3D printing material from plastic to metal. In this case, a motor with higher torque may be required and the device weight may increase. The other solution is to use extendable mechanisms with low stretch ratios. For a reachable length of about 1.0-1.5 times the distance from elbow to fingertip, a low stretch ratio may be acceptable to maintain the compact size.

Second, a higher comfort level for wearing the device was expected. There was some feedback about the use comfort, such as “the weight is a little bit heavy”, and “the pressure is concentrated at the area above the elbow”. This mainly occurred among female participants, which skewed the evaluation results for comfort. To resolve this issue, we are considering two feasible solutions: (a) use cushion material to relieve the pressure, and (b) use an extra harness fixed to the trunk to spread the pressure over the whole body.

Third, a controller with high operability was preferred. Although the high controllability is out of our research scope, this has resulted in a negative user experience in the user study. A possible solution is to employ bio signal sensors instead of the current button controller, such as Electromyography (EMG) sensors. This can enable users to control the wearable robot arm more flexibly, with the possibility of introducing wireless communication to the control board.

6 CONCLUSION

In this work, we proposed a wearable robot arm with storability and extendibility for human augmentation. To verify the proposed system, we developed a compact robot arm prototype. In our user study, we evaluated the device performance based on users’ feedback from their experience while wearing the prototype and a post-experience questionnaire.

For future work, we would like to improve robot control from two aspects. First, we plan to improve robot control by finding a reasonable center of mass with a minimum burden on the user. Second, we can employ a controller that fits ergonomically and control it with biological information such as an EMG sensor for muscle signals. There is a possible solution to optimize the overall structure by decreasing the device weight and enhancing the bending strength of the extendable mechanism. The proposed device can be more flexible by increasing the degrees of freedom. A typical weakness of wearable robot arms is the limited weight that can be lifted. One feasible solution is to increase the payload through structure and material optimizations.

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