

## Development Report:

# Development and Evaluation of Arm Lifting Assist Devices

Ryota Jitsukawa, Hiroshi Kobayashi, Kenta Matsumoto, and Takuya Hashimoto

Department of Mechanical Engineering, Tokyo University of Science

6-3-1 Nijjuku, Katsushika-ku, Tokyo 125-8585, Japan

E-mail: {r-jitsukawa, hiroshi, kmatsumoto}@kobalab.com, tak@rs.tus.ac.jp

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**Musculoskeletal disorders are common occupational diseases that have become a major social problem. Mechanization has been promoted as a solution to this problem. However, several tasks still require manual labor, such as fruit harvesting in orchards, making the introduction of machinery difficult in many cases. Recently, from the viewpoint of worker protection and ergonomics, various wearable robots for work support have attracted attention. In Europe and the US, there has been much development of arm-lifting assistive devices that support upward work while holding tools in the hands for industrial applications. However, most of the devices currently on the market are expensive compared to their assistive capabilities. Against this background, we developed three types of arm-lifting assistive devices with different concepts (an exoskeleton arm-lifting assistive device utilizing a gas spring, an exoskeleton arm-lifting assistive device utilizing McKibben-type artificial muscles, and an arm-lifting assistive suit utilizing rubber) to develop inexpensive, high-power devices. Furthermore, comparative verification of the assist effectiveness of each device was conducted.**

**Keywords:** arm-lifting assist device, exoskeleton, endoskeleton, EMG

## 1. Introduction

Because of recent developments in mechanical technologies, simple human work has been automated to release workers from physical fatigue. However, plenty of fieldwork remains difficult to mechanize in the agriculture and construction industries. Such work environments can cause musculoskeletal disorders [1, a].

Under these circumstances, various wearable work-assist robots have attracted attention from the perspectives of worker protection and ergonomics. In some European countries and the US, arm-lifting assistance devices that support workers' extended arm work with tools held in their hands have been actively developed for industrial application [b]. The mainstream arm-lifting assist devices under development in these countries are passive devices that utilize no electric power such that they

are characteristically lightweight and easy for the wearer to move. AIRFRAME by Levitate Technologies Inc. utilizes springs for power, weighs 2.4 kg, and is priced at \$4,000 [2, 3, c]. EVO by Ekso Bionics utilizes gas springs (GS), weighs 3.7 kg, and is priced at \$5,000 [4, d]. The above-mentioned arm-lifting assist devices and many others currently available on the market have the above-mentioned characteristics and are priced very high [5–11, e–j]. In terms of the support forces of their devices, while most manufacturers have published no specific numerical values for their support forces, their support forces seem to be as large as the arms' self-weights because support forces that are too large would lift the arms. In the above-mentioned context, here, to develop such arm-lifting assist devices that are as simple and easy for their wearers' movements, affordable, and capable of generating appropriate support forces, we have developed arm-lifting assist devices with three different concepts: (1) an exoskeleton-type arm-lifting assist device utilizing GS (hereinafter, GS model), (2) an exoskeleton-type arm-lifting assist device utilizing McKibben-type artificial muscles (hereinafter, artificial muscle model), and (3) endoskeleton-type arm-lifting assist suits utilizing rubber (hereinafter, rubber model). In addition, to verify the effectiveness of the above-mentioned arm-lifting assist devices, we conducted comparative evaluations, where we examined the muscle usage with surface electromyograms and compared them between the cases of wearing no assist devices and wearing the above-mentioned three kinds of assist devices.

The GS model was commercialized as “Muscle Suit GS-ARM” by Innophys Co., Ltd. in May 2021 [k].

## 2. Development of GS Model

### 2.1. GS Model Concept

As illustrated in **Fig. 1**, this assist device adopts a GS, which is compact in size and lightweight, and yet a large reaction force can be expected. The GS, comprising a cylinder, rod, and installation parts, has a high-pressure gas sealed inside. The rod is pushed into the cylinder to compress the interior high-pressure gas and generate a reaction force. Because the GS has a large initial reaction force, its reaction force gently increases in proportion to its pushed-in amount (stroke). The adopted GS has an



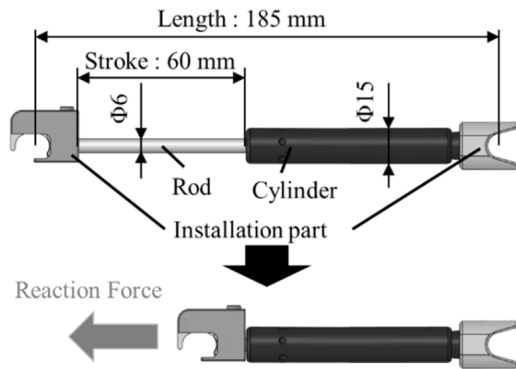


Fig. 1. Gas spring applied.

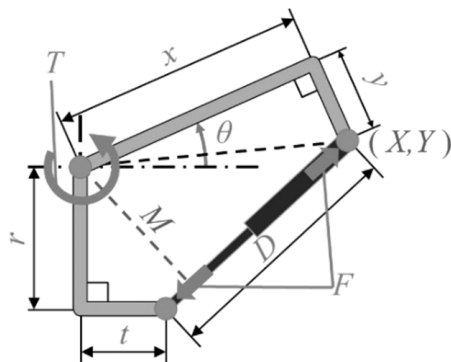


Fig. 2. Four-bar slider link mechanism.

initial reaction force of 290 N, maximum reaction force of 390 N, length of 185 mm (between the shaft holes at the installation parts), stroke of 60 mm, and mass of 89 g. Support forces were generated utilizing this GS as a sliding pair of the four-bar slider link mechanism presented in Fig. 2.

## 2.2. Overview of GS Model

Figure 3 illustrates the external and wearing appearance of the GS model. The GS stored in each left and right arm comprised the back, waist, and other belts. Axis (a) is an active rotation axis that generates the support torque by the GS. An arm pad was placed at the tip of the arm via the passive rotation axis (b). In the back part, the back frame was connected to the waist belt via rod-end bearings. Body weight, including the cover, was 3.2 kg.

## 2.3. Support Torque (GS Model)

The support torque  $T$  generated by the GS can be expressed by Eq. (1) utilizing the parameters  $(x, y, t, r)$  presented in Fig. 2. When the arm is horizontal to the ground, its angle  $\theta$  is  $0^\circ$  and upward positive.

$$T = FM = F \left( r + t \frac{Y+r}{X-t} \right) \frac{X-t}{D}. \quad (1)$$

Then, the moment arm  $M$  can be expressed as follows utilizing the values presented in Fig. 2:

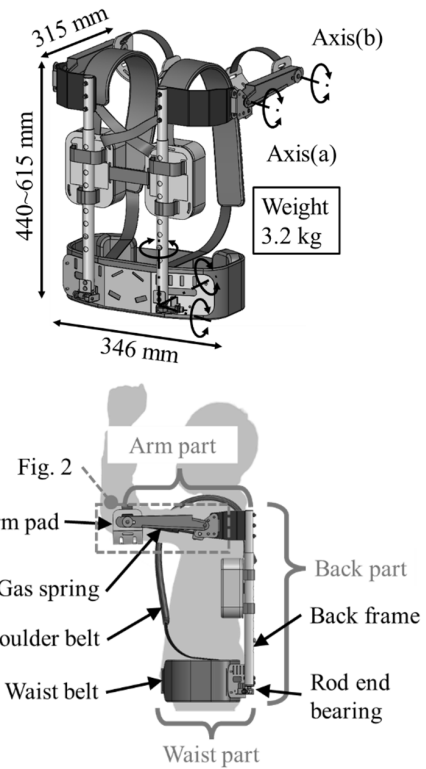


Fig. 3. GS model.

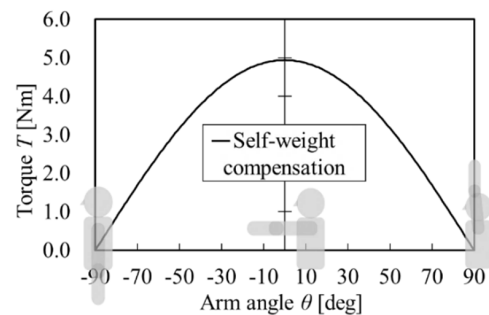


Fig. 4. Self-weight compensation.

$$\alpha = \tan^{-1} \left( \frac{y}{x} \right), \quad (2)$$

$$\beta = \tan^{-1} \left( \frac{X-t}{Y+r} \right), \quad (3)$$

$$l = \sqrt{x^2 + y^2}, \quad (4)$$

$$X = l \cos(\theta - \alpha), \quad (5)$$

$$Y = l \sin(\theta - \alpha), \quad (6)$$

$$D = \sqrt{(X-t)^2 + (Y+r)^2}, \quad (7)$$

$$c = \frac{t}{\tan \beta}, \quad (8)$$

$$M = (r+c) \sin \beta = \left( r + t \frac{Y+r}{X-t} \right) \frac{X-t}{D}. \quad (9)$$

First, we designed it such that its self-weight is compensated against the arm's weight. Fig. 4 presents the torques which are necessary for self-weight compensa-

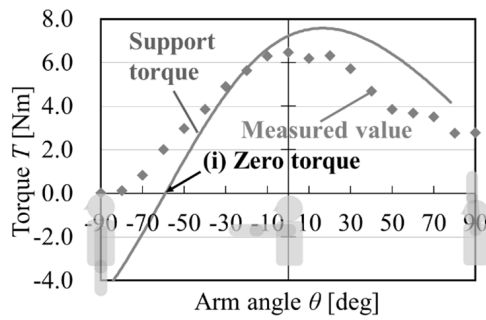


Fig. 5. Support torque (GS model).

tion by assuming the arm to be a rigid bar weighing 3 kg. We prototyped a device with such support forces for evaluation and found that its wearers did not feel sufficient support when lifting their arms. When they lift their arms, some muscles serve as resistance; therefore, torques larger than the simple self-weight compensation are required.

Therefore, the torques around the shoulders of ten participants required to support their arms were measured. Specifically, we calculated the torques from the products of multiplying the lengths from the shoulder joints to the measuring points by measuring the force gauge pressed vertically near the participants' elbows and the arm pad contacts with their enervated arms. The angles of the upper arms were simultaneously measured utilizing a digital angle meter. In Fig. 5, the dotted line indicates the mean measured values, and the solid line indicates the theoretical support force values empirically determined based on the mean measured values. In Fig. 5, the domain  $-90^\circ \leq \theta \leq 75^\circ$  represents the device's movable range and the range beyond the point where support torque  $T = 0$  Nm as indicated by (i) in Fig. 5 ( $-60^\circ \leq \theta \leq 75^\circ$ ), the device's working area. As illustrated in Fig. 5, the device generated larger support torques than the measured values, which enabled the participants to experience sufficient support forces when the parameters were  $x = 170$ ,  $y = 0$ ,  $t = 12$ , and  $r = 20$  mm. As for the support torques at  $\theta < 0^\circ$ , they are described in the following subsection.

## 2.4. Lock System (GS Model)

Placing any arm-lifting assist device in practical application is an important element that can be easily mounted and dismounted. Therefore, the GS model was structured to lock its arm downward when mounted and dismounted. Fig. 6 illustrates the principles of the lock system. The support torque  $T = 0$  Nm at point (i) in Fig. 5 is attributable to the fact that the link mechanism constitutes a change point at  $\theta = -60^\circ$ , as presented in Fig. 6. By lowering the arm further from that point, the support torque becomes negative such that the arm part rotates to its movable limit area and stops there. Subsequently, it was completely locked by buckling via a belt connected to the waist.

This lock system is a safety mechanism to avoid the risk of the arm leaping beyond the change point during a

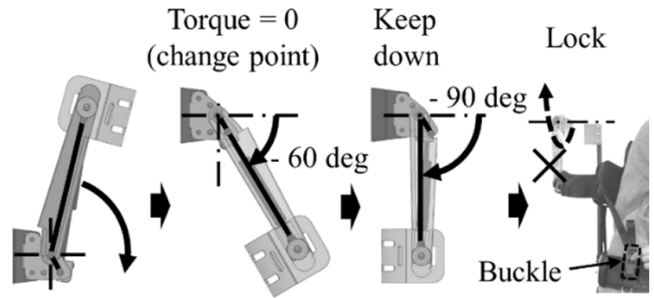


Fig. 6. Lock system (GS model).

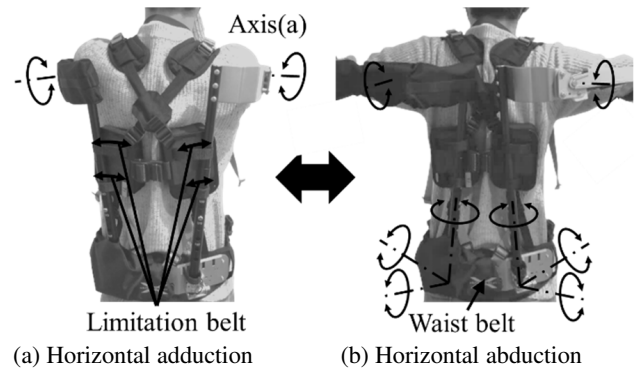


Fig. 7. Flexible movement of GS model.

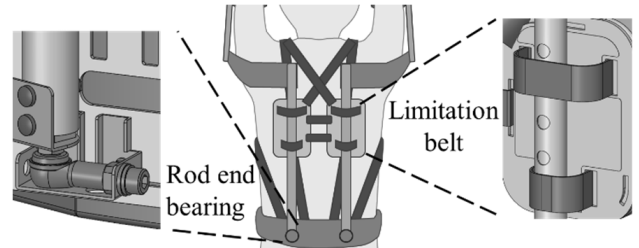


Fig. 8. Belt structure.

sudden collision. When the device is utilized again, the wearer disengages the buckle and lifts its arm beyond the change point.

## 2.5. Belt Structure

Figures 7(a) and (b) illustrate the horizontal adduction and horizontal abduction movements of the GS model wearer's arm, respectively. Because the position of the shoulder joint's rotation axis varies with the arm's movements, axis (a) needs to follow the human shoulders to improve its mobility. Therefore, as illustrated in Fig. 8, rod-end bearings at the bottom of the back frame were arranged so that the entire device could move to the waist belt with three degrees of freedom.

Because its movements must be limited to prevent it from loosening from the body, the limitations were provided, as presented in Fig. 8. Thus, the structure we have realized has the mobility to respond to the wearer's various movements.

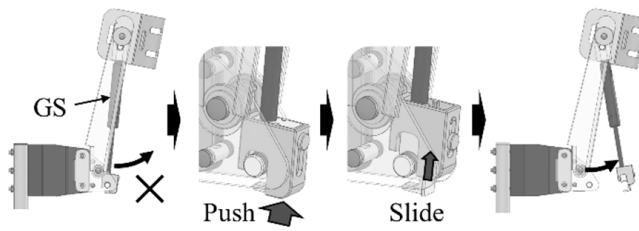


Fig. 9. GS exchange mechanism.

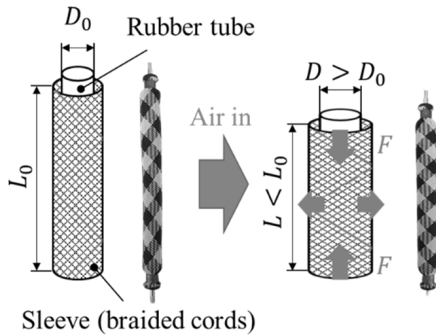


Fig. 10. Artificial muscle.

## 2.6. GS Exchange Mechanism

In the GS model, the GS must be exchanged when the support torque is altered or the device deteriorates owing to gas leakage inside the GS cylinder. Considering that GS is exchanged by consumers unfamiliar with machinery, we devised a structure that allows them to exchange GS as simply as possible without any tools. **Fig. 9** illustrates the structure adopted for the GS exchange mechanism, where we can easily exchange the GS by simply pushing its protruding part with a finger and sliding it. The timing to exchange the GS unit of “Muscle Suit GS-ARM” is about one year as a guide, which, however, varies with its application frequency [k].

## 3. Development of Artificial Muscle Model

### 3.1. Artificial Muscle Model Concept

As described in Section 2.6, the GS model requires a mechanism to exchange the GS itself when GS deteriorates or when its support force is to be altered, which can potentially increase its costs. In the artificial muscle model, to generate support forces that suit its users by means of an actuator with excellent durability, a McKibben-type artificial muscle, whose output varies with the sealed pneumatic pressure, was adopted as illustrated in **Fig. 10**.

The artificial muscle is structured as a rubber tube covered with a sleeve made from polyester monofilament and swaged at both ends; although compact in size and light in weight, it generates strong contractile forces in the longitudinal direction. The artificial muscle utilized here is 230 mm in equilibrium length, when its outside diameter

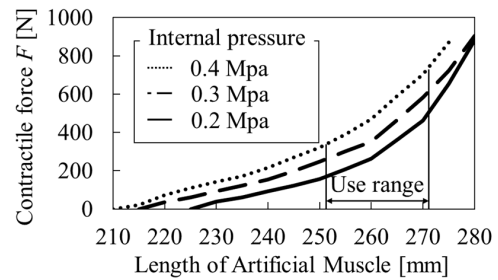


Fig. 11. Contractile force of artificial muscle.

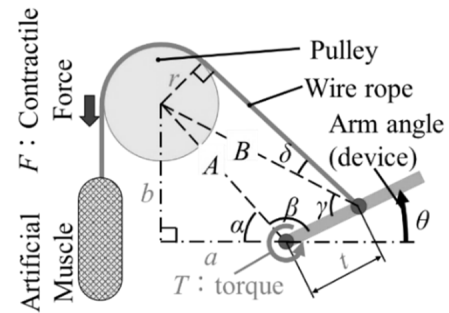


Fig. 12. Mechanism (artificial muscle model).

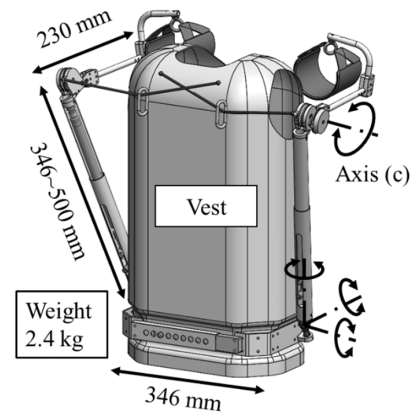


Fig. 13. Artificial muscle model.

is 17.3 mm. **Fig. 11** illustrates the output characteristics and usage range of the adopted artificial muscle. As illustrated in **Fig. 12**, the artificial muscle model generated its support torque by lifting the arm frame with the artificial muscles via a pulley and wire rope.

### 3.2. Overview of Artificial Muscle Model

**Figure 13** presents the external appearance of the developed artificial muscle model, and **Fig. 14** illustrates its wearing state. It comprises two side frames, one on the left and right sides, an arm part, a waist, and a vest. One piece of artificial muscle is stored in each left and right frame, and air is supplied via a tube by a manual pump. The worker keeps supplying air until they feel a proper support torque has been obtained; if they feel a lack of support torque during work, they supply air with the manual pump once again. Axis (c) is the active rotation axis

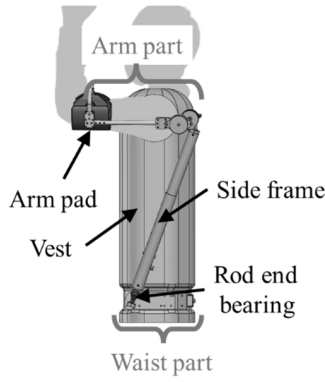


Fig. 14. Wearing of artificial muscle model.

that generates the support torque from the artificial muscle. The arm pad hangs from the PP belt at the tip of the arm. The side frames are connected to the waist utilizing rod-end bearings. The artificial muscle model body weighs 2.4 kg.

### 3.3. Support Torque (Artificial Muscle Model)

The support torque  $T$  around axis (c) generated by the artificial muscles can be calculated by determining the four parameters ( $a$ ,  $b$ ,  $r$ ,  $t$ ) presented in Fig. 12 and can be expressed by Eq. (10) for the arm part angle of the model.

$$T = Ft \sin(\gamma + \delta) \quad (10)$$

where the respective values can be expressed as follows from the values presented in Fig. 12:

$$A = \sqrt{a^2 + b^2}, \quad (11)$$

$$\alpha = \tan^{-1} \left( \frac{b}{a} \right), \quad (12)$$

$$\beta = \pi - \alpha - \theta, \quad (13)$$

$$B = \sqrt{A^2 + t^2 - 2At \cos \beta}, \quad (14)$$

$$\delta = \sin^{-1} \left( \frac{r}{B} \right), \quad (15)$$

$$\gamma = \sin^{-1} \left( \frac{A \sin \beta}{B} \right). \quad (16)$$

Based on the support torque of the GS model, the parameters are set as follows:  $a = 22$ ,  $b = 20$ ,  $t = 17$ , and  $r = 20$  mm. The contractile force of an artificial muscle varies with the internal pressure. As an example where pneumatic pressures of 0.2, 0.3, and 0.4 MPa are supplied at the arm part's flexural upper limit angle  $\theta = 40^\circ$ , Fig. 15 demonstrates the relations between the device's arm part angle  $\theta$ , wearer's arm angle  $\varphi$ , and the support torque  $T$ . In Fig. 15, where the domain  $-90^\circ \leq \theta \leq 40^\circ$  represents the device's movable range and the change point indicates the lower limit in the movable range, the working range comes between the domain's upper limit and the change point: the arm angles in the working range are  $-65^\circ \leq \varphi \leq 70^\circ$  as described below. As this device is structured as for the side frames to be able to freely

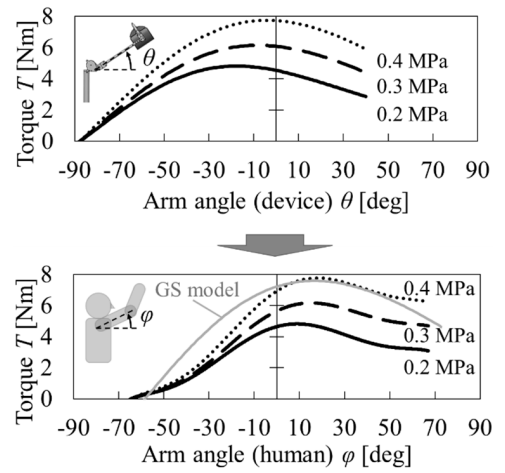


Fig. 15. Support torque (artificial muscle model).

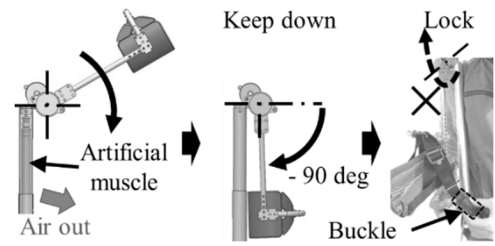


Fig. 16. Lock system (artificial muscle model).

move by the rod-end bearings in the case of the shoulders' flexion and extension movements, angles  $\theta$  and  $\varphi$  are not identical. Therefore, we have estimated the relations between the wearer's arm angle  $\varphi$  and the support torque  $T$  by verifying the relations between angles  $\theta$  and  $\varphi$  in the case of wearing this device. By the way, in lowering the arm from the horizontal ( $\varphi = 0$ ), while the force  $F$  in Eq. (10) increases as the artificial muscle is extended, the support torque  $T$  consequently gets smaller as the angle  $(\gamma + \delta)$  decreases such that the increase in  $F$  should not hinder the wearer's lowering their arm.

### 3.4. Lock System (Artificial Muscle Model)

From the perspectives of usability and safety, similar to the GS model, we structured the device such that its arm part is locked downward when mounted and dismounted. Fig. 16 illustrates the principles of the lock system. First, the air supplied to the artificial muscle was released to decrease the support torque. Next, lower the arm to lower the device's arm part down to the arm's movable limit range ( $\theta = -90^\circ$ ). It was then completely locked by buckling via belts connected to the waist. When arm-lifting work is resumed, the buckle is disengaged, and air is supplied again.

### 3.5. Vest Structure

Under the design conditions that the device should allow its wearer's easy movements and that it should

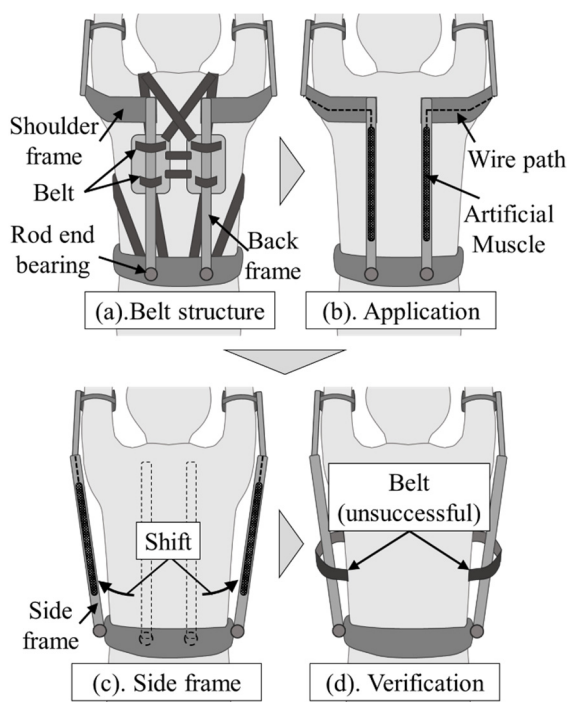


Fig. 17. Flow of structure determination.

be structured not to become loosened from the wearer's body, for the GS model, a belt structure was adopted that restricts the back frame's movements by the belts that are in close contact with the wearer's body (see Section 2.5). For the artificial muscle model, in contrast, we adopted a vest structure that restricts the side frame's movements by the vest and elastic cords, described below.

First, for the GS model, as shown in Fig. 17(a), we adopted shoulder frames such that they would contact the wearer's body as closely as possible. Suppose that such shoulder frames are adopted for the artificial muscle model, as illustrated in Fig. 17(b). In this case, the wire paths connected to the artificial muscles become complex and increase the number of components. Therefore, we simplified the structure by removing the shoulder frames and adopting side frames instead of shifting the back frame to the sides of the wearer's body, as illustrated in Fig. 17(c). Like the GS model, as the side frames are connected to the rod-end bearings and must be restricted not to move too far away from the wearer's body, we have installed the belts, as illustrated in Fig. 17(d), to find, however, that whatever arrangements of the belts to the side frames are difficult to secure the wearer's ease of movements. Therefore, we adopted a vest and elastic cords, as illustrated in Fig. 18, to restrict the side frames' movements so as not to get too far from the wearer's body by generating tensions to pull them toward the body center, as well as to secure the wearer's ease of movement.

Figure 19 illustrates the arm movements of the artificial muscle model wearer: (a) horizontal adduction and (b) horizontal abduction. Fig. 19 demonstrates that we have realized a structure that does not hinder the wearer's movements but can secure their ease of movement.

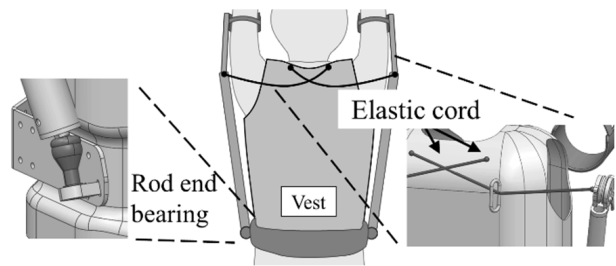


Fig. 18. Vest structure.

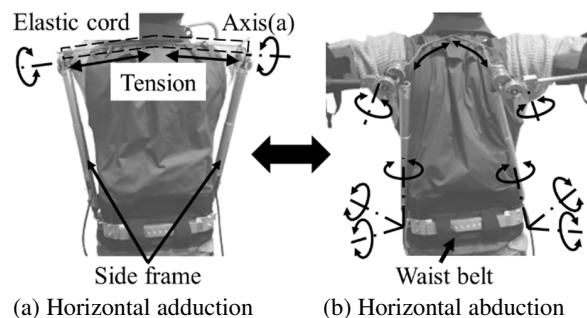


Fig. 19. Flexible movement of artificial muscle model.

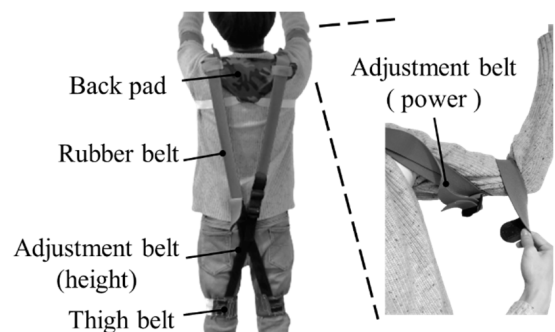


Fig. 20. Rubber model.

## 4. Development of Rubber Model

### 4.1. Rubber Model Concept

The two above-mentioned models have realized sufficiently large support forces to support human arms. In the case of large support forces, assistive devices inevitably need to be exoskeletal, large, or heavy. Therefore, in the rubber model, we attempted to make it lightweight and compact, though small in generated support force, by utilizing no metal components but mainly sewn ones. For the power, we utilized rubber belts that could generate a tension of 20 N at an elongation percentage of 150%.

### 4.2. Overview of Rubber Model

Figure 20 illustrates the external appearance of the rubber model. It is simply configured so that its wearers carry a back pad on their backs, which is obliquely connected to their thighs and upper arms by height-adjusting PP and rubber belts. A rubber belt was wound around the upper arm from the inside. A support-force adjustment belt was

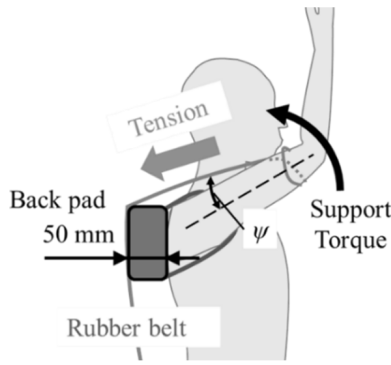


Fig. 21. Mechanism (rubber model).

installed near the interior of the upper arm. The rubber model's body weighs as light as 0.32 kg.

### 4.3. Mechanism (Rubber Model)

Figure 21 reveals that the support forces were generated in the shoulder flexion direction by the tension of the rubber belt. The thicker the back pad is, the larger support forces are generated because of the increased angles  $\Psi$  between the rubber belt and the arm. However, considering the case in which the rubber model is employed in a narrow space, the back pad thickness was empirically set to 50 mm.

## 5. Comparative Evaluation of Each Device

### 5.1. Evaluation by Surface Electromyogram

Surface electromyography (EMG), which refers to a method of reading faint action electric potentials that are locally generated by muscle fibers (muscle potentials) with electrodes stuck on the surfaces of the muscles to be measured, is generally utilized to evaluate muscle usage and muscle fatigue [12]. This method is often employed to evaluate the assistive effects of wearable robots [2–11, 13].

We comparatively evaluated the respective assistive devices by measuring their EMGs. We stuck wet-type disposable electrodes (made by Parama-Tech Co., Ltd.) and utilized EMG Logger II (Logical Product Corp.) for the measurements. Because the EMG's effective frequency band is generally set at 5–500 Hz [14], we utilized a sampling frequency of 1 kHz, a low-pass filter of 450 Hz, and a high-pass filter of 20 Hz as the cut-off frequencies. To evaluate muscle usage, the average rectified values (ARVs) of the measured EMGs were firstly obtained and integrated to obtain an integral electromyogram (IEMG). With  $(-T, T)$  denoting a calculation section,  $t$ , time, and  $\tau$ , time constant, ARV and IEMG are given by the following equations.

$$ARV(t) = \frac{1}{2T} \int_{-T}^T |S(t + \tau)| d\tau \quad (17)$$

$$IEMG = \sum ARV(t) \quad (18)$$

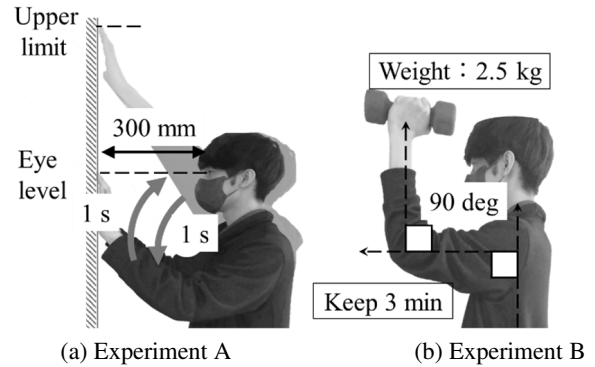


Fig. 22. Experimental operation.

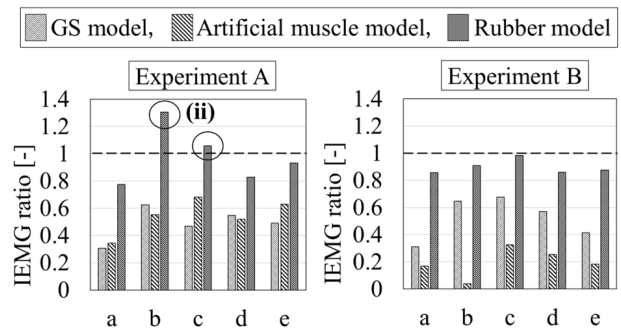


Fig. 23. IEMG ratio.

### 5.2. Evaluation Method

We conducted two experiments, A and B, with five healthy male and female participants (a)–(e) in their 20s (1) without any assist device, (2) with GS model, (3) with artificial muscle model, and (4) with rubber model, and measured their EMGs at the anterior parts of the deltoid muscles, which made the greatest contributions to the shoulder's flexion movements [15]. In experiment A, as illustrated in Fig. 22(a), each participant, standing 300 mm away from the wall with no weight held in their hand, made dynamic movements by lifting their arm from their eye level to the upper limit and lowering it. In experiment B, as illustrated in Fig. 22(b), each participant held a weight of 2.5 kg in their hand, standing in a posture where their elbow was flexed at 90° from their horizontally retained upper arm, and retained the posture for up to 3 min, whereas in the artificial muscle model, air was supplied until the participant felt just right.

### 5.3. Evaluation Results and Considerations

Figure 23 presents the evaluation of the experimental results: IEMG ratios of the GS model, artificial muscle model, and rubber model to one set as the IEMG value for the case without an assistive device. The IEMG refers to the sum of the ARVs from the start to the end of the movement, the time of which was identical in each experiment. Any IEMG ratio below 1 indicates support effects, and those above 1 indicate the application of superfluous muscles.

Regarding the GS and artificial muscle models, experiments A and B revealed reduced muscle usage. In particular, the artificial muscle model, which could regulate its support forces, was found to have extremely high support effects in static movements (experiment B)

Although the rubber model is inferior to the other two models, the experiments have found that it has some support effects, but with some exceptions. Although we note from (ii) in **Fig. 23** that the muscle usages of participants (b) and (c) have increased from those without any assist device in experiment A, in the post-experimental hearings of the participants, they evaluated the rubber model to the effect that their movements have been eased by wearing it, which seems attributable to the fact that because muscles other than the anterior deltoids are complicatedly entangled in the shoulder's flexion and extension movements, the muscle usages of the other muscles than those we have measured this time have been reduced.

## 6. Conclusion and Prospects

### 6.1. Conclusion

As recent years have seen an increasing demand for wearable robots to assist workers, multiple arm-lifting assist devices to support workers' extended arm work have been commercialized; however, they are expensive. Therefore, here, to develop affordable and effective assist devices, we developed and evaluated three types of arm-lifting assist devices: (1) an exoskeleton-type arm-lifting assist device utilizing GS, (2) an exoskeleton-type arm-lifting assist device utilizing McKibben-type artificial muscles, (3) and an endoskeleton-type arm-lifting assist device utilizing rubber.

As for (1) the GS model, we have realized a simple structure by adopting a four-bar link mechanism utilizing GS and have commercialized "Muscle Suit GS-ARM," which can generate a maximum support force of 4.5 kg (maximum torque of 7.5 Nm) per arm and is priced at JPY 149,600, which is less expensive than the other commercially available products. For (2) the artificial muscle model, we realized an assist device of variable support forces with a simple mechanism in which the arms of the workers are lifted by McKibben-type artificial muscles via a pulley and wire. For (3) the rubber model, unlike the above-mentioned two models, we adopted an endoskeleton-type suit structure to realize a drastic light-assisted device, although its generated support forces were small.

In addition, we evaluated the support effects of the above-mentioned three types of assist devices utilizing surface electromyograms and checked their applicability.

### 6.2. Prospects

In the future, we need to evaluate these assistive devices in fieldwork, where workers are asked to wear them in their actual fields for a long time. Based on feedback from such fieldwork, we plan to further improve them. More-

over, we will put them into early practical application by improving their structures, reducing their weight, and improving their usability concurrently with endurance tests.

Although some European countries and the US have advanced the development of arm-lifting assist devices, Japan is gradually catching up with them. The authors intend to implement the abovementioned improvement plans for our developed arm-lifting assist devices as soon as possible.

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**Name:**  
Ryota Jitsukawa

**Affiliation:**  
Department of Mechanical Engineering, Graduate School of Engineering, Tokyo University of Science

**Address:**  
6-3-1 Niijuku, Katsushika-ku, Tokyo 125-8585, Japan  
**Brief Biographical History:**  
2022- Master's Student, Tokyo University of Science



**Name:**  
Hiroshi Kobayashi

**Affiliation:**  
Professor, Department of Mechanical Engineering, Tokyo University of Science

**Address:**  
6-3-1 Niijuku, Katsushika-ku, Tokyo 125-8585, Japan  
**Brief Biographical History:**  
1996- JSPS Overseas Fellow, AI Laboratory, University of Zurich  
1998- Lecturer, Tokyo University of Science  
1999- Associate Professor, Tokyo University of Science  
2008- Professor, Tokyo University of Science  
**Main Works:**  
• Exoskeleton and image processing.  
**Membership in Academic Societies:**  
• The Japan Society of Mechanical Engineers (JSME)  
• The Robotics Society of Japan (RSJ)  
• Institute of Electrical and Electronics Engineers (IEEE)



**Name:**  
Kenta Matsumoto

**ORCID:**  
0000-0003-4449-8093

**Affiliation:**  
Assistant Professor, Department of Mechanical Engineering, Faculty of Engineering, Tokyo University of Science

**Address:**  
6-3-1 Niijuku, Katsushika-ku, Tokyo 125-8585, Japan  
**Brief Biographical History:**  
2018 Received Ph.D. degree from Doshisha University  
2018- Research Fellowship, Organization for Research Initiatives and Development, Doshisha University  
2019- Assistant Professor, Tokyo University of Science  
**Main Works:**  
• "Evaluation of the power assist effect of muscle suit for lower back support," IEEE Access, Vol.9, pp. 3249-3260, 2021.  
• "Analysis of golf swings of varying skill level using singular value decomposition," ISEA Engineering of Sport 14 Conf., 2022.  
**Membership in Academic Societies:**  
• The Japan Society of Mechanical Engineers (JSME)



**Name:**  
Takuya Hashimoto

**ORCID:**  
0000-0001-7190-8233

**Affiliation:**  
Department of Mechanical Engineering, Tokyo University of Science

**Address:**  
6-3-1 Niijuku, Katsushika-ku, Tokyo 125-8585, Japan  
**Brief Biographical History:**  
2009-2012 Assistant Professor, Tokyo University of Science  
2013-2015 Assistant Professor, The University of Electro-Communications  
2016-2021 Junior Associate Professor, Tokyo University of Science  
2021- Associate Professor, Tokyo University of Science  
**Main Works:**  
• "Evaluation of the power assist effect of muscle suit for lower back support," IEEE Access, Vol.9, pp. 3249-3260, 2021.  
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**Membership in Academic Societies:**  
• Institute of Electrical and Electronics Engineers (IEEE)  
• The Japan Society of Mechanical Engineers (JSME)  
• The Robotics Society of Japan (RSJ)  
• Human Interface Society (HIS)