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# Weight reduction and development of exoskeletal lumbar assist suits

Hibiki Nagasawa[1†], Tomoya Yoshida[2], Ryota Sato[3], Hiroshi Kobayashi[4] and Takuya Hashimoto[5]

[1]Graduate School of Engineering, Tokyo University of Science, Tokyo, Japan
(Tel: +810-5876-1717; E-mail: n.hibiki@kobalab.com)
[2]Graduate School of Engineering, Tokyo University of Science, Tokyo, Japan
(Tel: +810-5876-1717; E-mail: tomoya.yoshida@kobalab.com)
[3]Graduate School of Engineering, Tokyo University of Science, Tokyo, Japan
(Tel: +810-5876-1717; E-mail: r-sato@kobalab.com)
[4]Graduate School of Engineering, Tokyo University of Science, Tokyo, Japan
(Tel: +810-5876-1717; E-mail: hiroshi@kobalab.com)
[5]Graduate School of Engineering, Tokyo University of Science, Tokyo, Japan
(Tel: +810-5876-1717; E-mail: tak@rs.tus.ac.jp)

**Abstract:** With advances in science and technology, much physical labor has been automated; however, physically demanding work that is difficult to mechanize still exists, and low back pain has become a serious global issue. The authors have developed and promoted the Muscle Suit as a countermeasure against back pain, but users are demanding further miniaturization and weight reduction. In this study, we reviewed the assistive torque and developed a new model targeting a total weight of 3 kg. This paper reports on the details of that development.

**Keywords:** Medical and Welfare Systems, Human Interfaces, Safety, Environment and Eco-Systems

## 1. INTRODUCTION

With the advancement of science and technology, many forms of physical labor have been automated. However, heavy-duty tasks that are difficult to mechanize remain in fields such as nursing care, construction, agriculture, and logistics. According to a survey by the Ministry of Health, Labour and Welfare of Japan, approximately 58% of work-related injuries requiring four or more days of rest in 2023 were due to low back pain[1]. Low back pain is also a serious global issue, affecting approximately 619 million people in 2020, and is projected to impact over 800 million people by 2050 [2]. Lumbar support suits, developed as a countermeasure against back pain, are broadly classified into "exoskeleton type" and "endoskeleton type."

The exoskeleton type[3-16] features a frame structure and provides a strong assistive force. In contrast, the endoskeleton type [17-21] does not have a frame and is made of flexible materials such as fabric or rubber, allowing it to be worn like regular clothing.

The authors have been continuously commercializing both exoskeleton[11-16] and endoskeleton[20, 21] types and they have been developing the exoskeleton type assistive device "Muscle Suit" using McKibben-type artificial muscles for the purpose of waist assistance since 2006. The mass-production model "Every" was launched in 2019 and became widely adopted. However, in response to demands for a lighter design, the "Exo-Power" was released in 2023. While improvements in walkability and miniaturization were achieved, the total weight remained at 4.3 kg, leaving further weight reduction as a challenge. Therefore, this study reports on the development of a new model with a target total weight of 3 kg by reviewing the assistive torque for the purpose of weight reduction.

## 2. OVERVIEW OF THE MUSCLE SUIT

### 2.1 Structure

Fig.1 shows a diagram of "Exo-Power". Exo-Power mainly consists of ① an upper body frame, ②artificial muscles, ③a waist belt, ④a biaxial part, ⑤a thigh frame, and ⑥thigh pads. The artificial muscles(②) are built into the upper frame(①). The artificial muscle is made of a rubber tube covered with a polyester monofilament sleeve, with both ends securely tightened. When compressed air is injected, it generates a strong contraction force in the longitudinal direction.

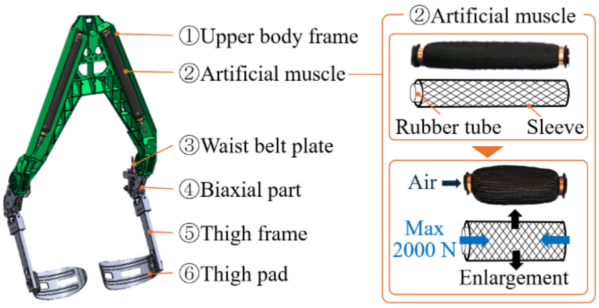

Fig.1 Structure of Exo-Power

### 2.2 Operating principles

Muscle suits can be classified into two types: active types which receive compressed air from an external compressor, and passive types in which air is manually pumped into the suit before use. "Exo-Power" is the latter. Fig.2 shows the principle of operation of "Exo-Power". When the wearer squats down with the artificial muscle filled with compressed air(about 0.2 MPa), the artificial muscle stretches, its internal volume decreases, and the internal pressure increases to approximately 0.5 MPa. This causes the artificial muscle to generate a contraction force, which is transmitted to the upper

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† Hibiki Nagasawa is the presenter of this paper.

body frame via pulleys and converted into torque relative to the thigh frame. This torque helps support the low back during movement.

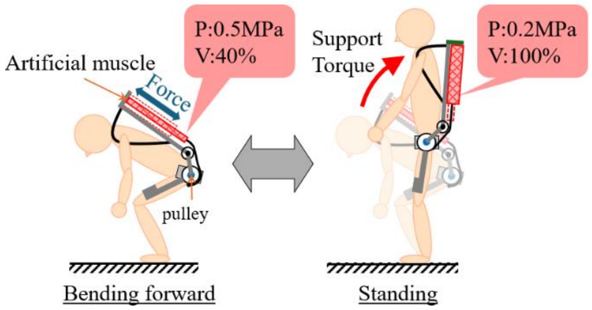


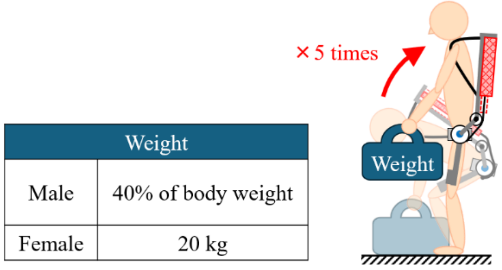
Fig.2 Assist mechanism of Muscle Suit

## 2. WEIGHT REDUCTION AND IMPROVEMENT

### 3.1 Review of maximum output

Considering that there is a limit to drastically downsizing a muscle suit composed of many parts, we focused on ways to reduce the rigidity of the device. By reviewing the auxiliary torque and reducing rigidity, the weight was reduced. In previous muscle suits, the maximum contraction force of the artificial muscle was 2000N and the maximum auxiliary torque was 100Nm. These values were obtained because of development up to that point and are not necessarily optimal. In this study, subjective evaluations were conducted with 13 male and female participants in their 20s. The experimental procedure is shown in Fig.3. During the experiment, participants performed lifting tasks while the assistive torque gradually increased by adjusting the air pressure. The objective was to determine the air pressure (torque) level at which the participants felt the assistance was sufficient. The weight of the load used in the experiment, as shown in Fig.3, was determined with reference to the maximum allowable weight for manual handling specified by the Ministry of Health, Labour and Welfare of Japan [22][23].

As a result of the evaluation, 12 out of 13 participants reported that the assistive force was sufficient even when the assistive torque was reduced by 20% (to 80 Nm) compared to the conventional model. Therefore, it was determined that an assistive torque of 80 Nm is adequate. To achieve this, the required maximum contraction force of the artificial muscle is 1600 N. Based on this, we explored the possibility of reducing the diameter of the artificial muscle while also pursuing structural weight reduction to the greatest extent possible.



| Weight | |
|---|---|
| Male | 40% of body weight |
| Female | 20 kg |

Fig.3 Experimental procedure

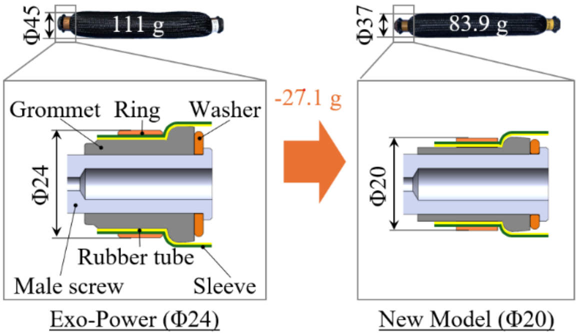


Fig.4 Change of dimensions of artificial muscle

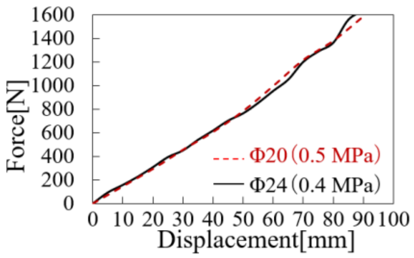


Fig.5 McKibben Artificial Muscle Output

### 3.2 Lightweight artificial muscle

The output of an artificial muscle is proportional to its cross-sectional area. Based on a review of the maximum output, the maximum contraction force was reduced from 2000 N to 1600 N in artificial muscles by reducing the diameter.

After trial and error, the artificial muscles were modified as shown in Fig.4. As shown in Fig. 4, the sealing diameter (cross-sectional diameter) at both ends of the artificial muscle was changed from Φ24 mm to Φ20 mm, and the braiding angle of the sleeve was adjusted. As a result, the displacement-output relationship of the Φ20 mm muscle at an internal pressure of 0.5 MPa became equivalent to that of the Φ24 mm muscle at 0.4 MPa, while achieving a maximum output of 1600 N (Fig. 5). By setting the displacement-output relationship to 80% of the previous configuration (achieved by reducing the pressure from 0.5 MPa to 0.4 MPa), the overall output profile of the device was also reduced to 80%. As a result, the artificial muscle achieved a weight reduction of 27.1 g (24.4%).

### 3.3 Lightweight upper body frame

The upper body frame accounts for a large portion of the muscle suit, so its weight reduction contributes to the overall weight reduction of the system. In this study, by revising the maximum output of the artificial muscle to 1600 N, we were able to achieve downsizing and weight reduction of the upper body frame.

The analysis conditions for the upper body frame assumed 500,000 usage cycles, and the allowable maximum stress was set to below 40 MPa based on the fatigue curve of resin B3WG6 (Fig. 6).Simulations were conducted using SOLIDWORKS Simulation (Dassault Systems SolidWorks) and ANSYS Mechanical (ANSYS) under the following three operating conditions (Fig.7: (1)-(3)).

(1) Maximum load generated when tightening waist belt: 100 N
(2) Torque generated during leg bending and opening/closing motion: 18.2 Nm
(3) Force acting during lifting operation (Artificial muscle: 1600 N, shoulder belt: 240 N, another auxiliary load: 120 N)

As a result, the width of the upper part of the upper body frame, which depends on the diameter of the artificial muscle, was reduced from 45 mm to 33 mm (Fig.8 A). Considering workability and weight reduction (by flattening the structure, stress is dispersed and the need for additional reinforcement is eliminated), the lower part of the upper body frame was flattened, reducing the overall frame thickness from 122 mm to 57.8 mm (Fig. 8B). The stress analysis results for the new model are shown in Table 1. The maximum stress was found to be below the target value of 40 MPa under all conditions. As a result, the weight of the upper body frame decreased by 277 g from 987 g to 710 g (28.1% reduction).

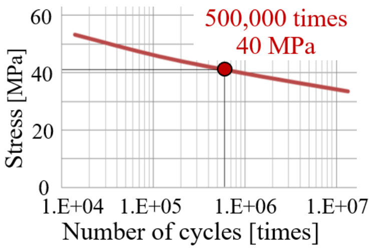


Fig.6 Fatigue curve (B3WG6)

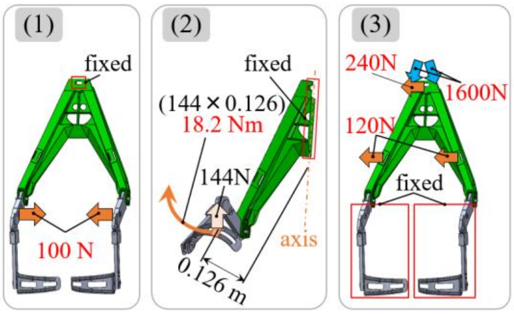


Fig.7 Upper body frame analysis conditions

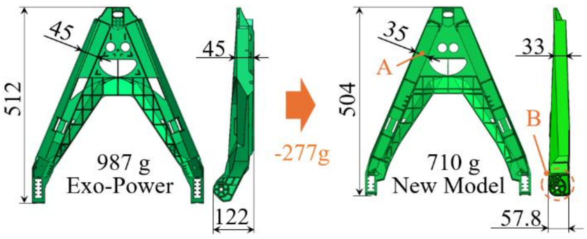


Fig.8 Various dimensions of upper body frame

Table 1 Upper body frame analysis results

| | Stress[MPa] | | | Displacement[mm] | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (1) | (2) | (3) |
| Exo-Power | 25.4 | 34.8 | 37.5 | 4.00 | 6.15 | 5.37 |
| New model | 33.6 | 35.7 | 38.6 | 6.10 | 5.90 | 6.94 |

### 3.4 Improvement of biaxial section

In accordance with the design change of the lower part of the upper body frame (Fig.8 B), three types of inter-axial distances for the biaxial part (④) were examined: 105 mm, 120 mm, and 135 mm. The results of the experiment are shown in Table 2. In the case of 135 mm, no interference was observed in all subjects, but the distance between the axes was excessive and there was concern about an increase in weight. In the case of 120 mm, interference was observed in one subject, but it was found to be caused by the subject's unique forward leaning posture with a rounded back, so the distance between the axes of 120 mm was adopted.

Table 2 Experimental results

| | Inter-Axial Distance [mm] | | |
|---|---|---|---|
| | 135 | 120 | 105 |
| Subject A (152 cm) | None | None | - |
| Subject B (167 cm) | None | Interference | Interference |
| Subject C (170 cm) | None | None | Interference |
| Subject D (178 cm) | None | None | Interference |
| Subject E (180 cm) | None | None | Interference |

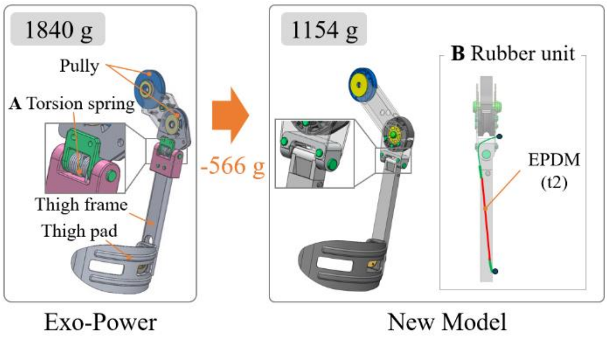


Fig.9 Lower body change

### 3.5 Weight Reduction of Lower Body

The conventional biaxial part (④) was composed of two plates, which increased the number of parts and made it difficult to secure rigidity. As a countermeasure, the new model uses a square pipe for the biaxial part to reduce weight and achieve high rigidity (Fig.9).

In the past, a torsion spring (Fig.9 A) was used in the thigh frame (⑤) to prevent the thigh frame (⑤) from rolling outward. However, because the component structure of the connecting part is more complicated, a new type of abduction prevention mechanism (Fig. 9 B) was adopted by passing an EPDM rubber unit inside the thigh frame and fastening both ends to the pulley and thigh frame with pins, respectively. The tension of the rubber always keeps the thigh frame in a position tilted approximately 5° in the abduction direction, and the tension pulls back the thigh frame during external rotation. This simplifies the structure of the thigh frame connection and reduces the number of leg parts, resulting in weight reduction. As a result, the total weight of the lower body was reduced by 568 g (30.9%) from 1840 g to 1272 g.

### 3.6 Gross weight

A weight comparison of each part with Every and Exo-Power is shown in Table 3. The total weight was reduced by 969 g (22.3%) from 4350 g to 3381 g compared to" Exo-Power".

Table 3 Total weight

| | Every [g] | Exo-Power [g] | New Model [g] |
|---|---|---|---|
| Upper Body Frame | 1260 | 984 | 710 |
| Lowe Body Parts | 1452 | 1840 | 1272 |
| Other | 1728 | 1526 | 1399 |
| Total (with Cover) | 4440 | 4350 | 3381 |

## 3. CONCLUSION

To reduce the weight of the muscle suit, the torque required to support the waist was re-examined. As a result, the maximum torque was determined to be 80 Nm, and a new model was designed. By reviewing the maximum torque, the weight of the artificial muscle (②) was reduced by 24.4%, and the size of the upper body frame (①) was reduced accordingly. As a result, the upper body frame (①) was 28.2% lighter.

As for the lower body, the biaxial part and the abduction prevention mechanism were improved, resulting in a 30.9% weight reduction of the entire lower body. As a result, the overall weight of the device was successfully reduced by 22.3%, bringing the total weight to 3,381 g, close to the target weight of 3 kg.

In the future, while pursuing further weight reduction, the durability and productivity of the device will be studied for mass production, and commercialization of the device will be promoted.

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