Paper:

Quantitative Performance Analysis of Exoskeleton Augmenting Devices – Muscle Suit – for Manual Worker

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Exoskeleton systems have been largely developed in spite that quantitative performance estimation has not been reported so far. Consequently, we have been developing the wearable muscle suit for direct and physical motion supports with relevant reports on the performance. The McKibben artificial muscle has introduced "muscle suit" compact, lightweight, reliable, and wearable "assist-bots" enabling users to lift and carry heavy objects. Applying integral electromyography (IEMG), we show the results of quantitative suit performance and posture-preserving efficiency. However, for practical use, lifting seems to be one of the most important tasks for users. We improve the forearm so that the muscle suit assists the user in vertical lifting. Load carrying and lifting experiments show the muscle suit's effectiveness.

Keywords: muscle suit, wearable robot, exoskeleton, McKibben artificial muscle, quantitative performance evaluation

1. Introduction

Human-powered devices have attracted attention in science fiction [1] and research for over 50 years. Science fiction has focused on augmenting the abilities of the healthy, especially in military use, while research has focused on assist bots for (i) augmenting able-bodied performance and (ii) implementing rehabilitation [2–15].

The term "exoskeleton" describes devices that augment able-bodied performance and designates certain assistive devices. The exoskeleton is worn fitting close to the body, working in concert with user movement.

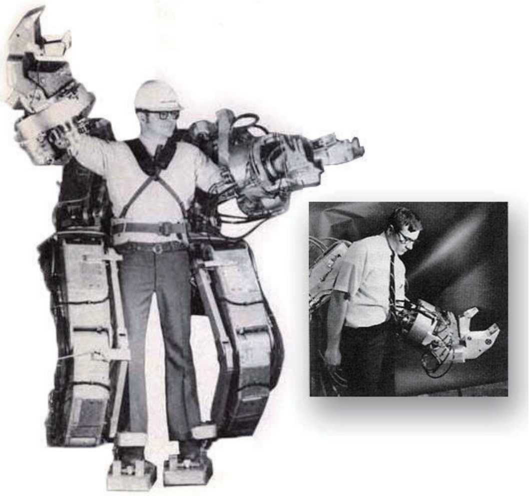


Fig. 1. Hardiman.

Hardiman (**Fig. 1** from the Human Augmentation Research and Development Investigation), developed in the 1960s, was one of the first full-body-powered exoskeletons – hydraulically powered, weighing 680 kg, and having 30 Degrees Of Freedom (DOF). It had components for amplifying the user's arm strength for the hands but not the wrists and legs of the user. Hardiman's purpose was to increase user strength 25 : 1 [16–19]. One arm eventually provided satisfactory results, but not the lower limbs, and the full-bodied device was never powered up with a user inside.

In the middle 2000 s, Sarcos Research Corporation (Salt Lake City, UT) developed a similar full-body exoskeleton – a "Wearable Energetically Autonomous Robot" (WEAR) working with the U.S. Defense Advanced Research Projects Agency (DARPA) Exoskeletons for Human Performance Augmentation (EHPA) program [20, 21]. WEAR carried its own power supply and had an advanced hydraulically activated exoskeleton operated by rotary hydraulic actuators on its powered joints.

WEAR successfully demonstrated such impressive feats as supporting a 84 kg load, enabling users to stand on one leg while carrying another person on their backs, walking at 1.6 m/s while carrying 68 kg on the back and 23 kg in the arms, walking through 23 cm of mud, and twisting, squatting, and kneeling [22]. Little further information on WEAR design or performance has, however, been made public.

The Berkeley Lower Extremity EXoskeleton (BLEEX), also developed under DARPA, was the first “load-bearing and energetically autonomous” exoskeleton [23]. BLEEX featured 3 DOF at the hip, 1 at the knee, and 3 at the ankle. It was activated via bidirectional linear hydraulic cylinders in a triangle with rotary joints, enabling effective moment arm that varied with the joint angle. BLEEX users could reportedly support a load of up to 75 kg while walking at 0.9 m/s loaded and at up to 1.3 m/s unloaded.

Japan’s University of Tsukuba full-body Hybrid Assistive Limb (HAL) realized an exoskeleton concept targeting both augmentation and rehabilitation [24–27]. HAL was activated by a DC motor with a harmonic drive directly on joints. HAL used by an able-bodied user, but not a physically challenged subject, was shown, together with its ability to increase user performance holding large loads in its arms, but the effectiveness of upper and lower limb components remains unclear.

A quasi-passive exoskeleton concept advanced at the Massachusetts Institute of Technology (MIT) Media Laboratory seeks to use passive human walking dynamics to create lighter, more efficient exoskeletons without using actuators to add strength to joints [28, 29]. The exoskeleton’s quasi-passive elements – springs and variable dampers – were chosen based on an analysis of walking kinetics and kinematics. Metabolic studies showed a 10% increase in the metabolic cost of transport for a user carrying 36 kg load versus a standard loaded backpack [30].

While results were not desirable, this is thought to be the first report on metabolic cost associated with walking by exoskeleton aid. No exoskeleton demonstrated thus far, however, reduces the metabolic cost of transport compared a standard backpack.

Exoskeleton use thus remains largely anecdotal.

Wearable muscle suits [31–35] developed to directly support upper body movement, as shown in **Fig. 2**, have enjoyed a different reception. Their purpose has been to help users needing assistance to move unaided. They are useful in rehabilitation and in aiding manual workers. The McKibben artificial muscle makes suits lightweight and practical.

The US National Institute for Occupational Safety and Health reports that manual tasks trigger work-related disorders such as back pain in 67% of nursing care personnel and 84% of automobile factory workers [36]. The European Agency for Safety and Health at Work reports that work-related disorders account for 30% to 46% of all work-related sick leave [37]. Considering income loss due to work-related disorders and / or industrial accident compensation makes work-related disorders a major issue.

Muscle suits were originally intended to aid the physically challenged, although practical use may be difficult in terms of ethics and safety, so we decided to apply these suits for use by manual workers to help solve the problem of work-related disorders.

The assistive or augmenting devices discussed above basically work in concert with user movement. While the muscle suit features the followings strategy “a human inside puts his or her weight and / or movement on muscle suits and / or movement of muscle suits.” Control is simple, i.e., giving the muscle suit the task-based movement pattern and controlling compressed air to artificial muscles. Unlike in other research, the strategy defines good quantitative performance as keeping a specific static posture with a load. That is, up to 85% reduction of Integral ElectroMyoGraphy (IEMG) was observed in this study [35]. Vertical lifting performance by the arms required to assist users has not, however, been estimated. With EMG the best known way to express the muscle strength used, we apply IEMG, time sequence change in IEMG, and a questionnaire for quantitative performance analysis.

Fig. 2. Suit overview.

This paper focuses on vertical lifting assistance and quantitatively evaluates performance. Section 2 discusses the muscle suit configuration and previous work, Section 3 explains suit improvements for supporting vertical movement and Section 4 shows the effects in vertical movement assist for keeping posture and lifting loads. Section 5 presents conclusions.

2. Suit Configuration

2.1. McKibben Artificial Muscle

The McKibben artificial muscle was selected as the muscle suit actuator thanks to its light weight, simple structure, softness, waterproof finish, and power-to-weight ratio [38]. The McKibben actuator was developed in the 1950s and 1960s in artificial-limb research [39].

The McKibben artificial muscle consists of an internal bladder surrounded by a braided mesh shell with flexible, nonexpandable threads attached at either end to fittings. As shown in **Fig. 3**, when the internal bladder is pressurized, air pushes against inner surfaces and against the external shell, expanding it. Due to the nonexpandability of threads in the braided mesh shell, the actuator is shortened as its volume increases and / or produces a load if it is coupled to a mechanical load. This results in 35%

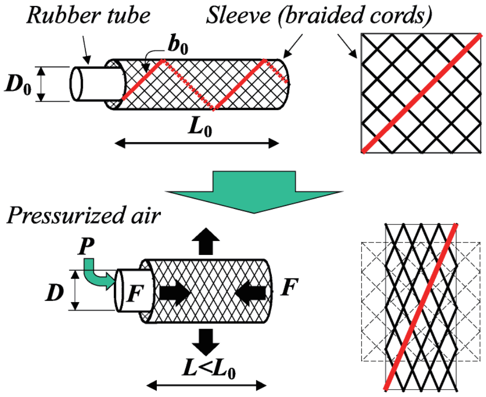


Fig. 3. McKibben artificial muscle structure.

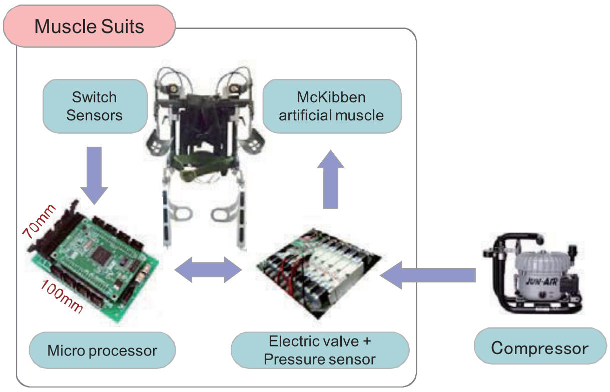


Fig. 4. System configuration.

contraction with no load and over 5% for a 150 kg load in case of 1.5 inch in diameter (D_0).

2.2. System Configuration

The McKibben actuator requires a compressor, microprocessor, and electric valve with a pressure sensor, as shown in **Fig. 4**. The electric valve controls compressed air output based on the microprocessor signal. The major drawback is the compressor. Since the factory where the muscle suit is to be used provides compressed air piping, however, we use it for the muscle suit by connecting tubing to piping. For use in the home, tubing could conceivably be supplied with compressed air from the ceiling so, from this standpoint, the muscle suit appears workable.

2.3. Muscle Suit Specifications and Effects

The muscle suit's mechanical structure must, above all, work smoothly with user movement. Assuming shoulder movement has 6DOF and the center of rotation changes with arm positioning, shoulder movement becomes complex, so we developed the special structure enabling shoulder movement shown in **Fig. 5** [38], using 4DOF for the shoulder – 3 orthogonal axes for rotation and a slider. Passive sliding follows changes in the center of shoulder rotation. **Table 1** lists muscle suit specifications. In addition to shoulder movement, 1DOF each is used for the elbow and sacroiliac to prevent low back pain.

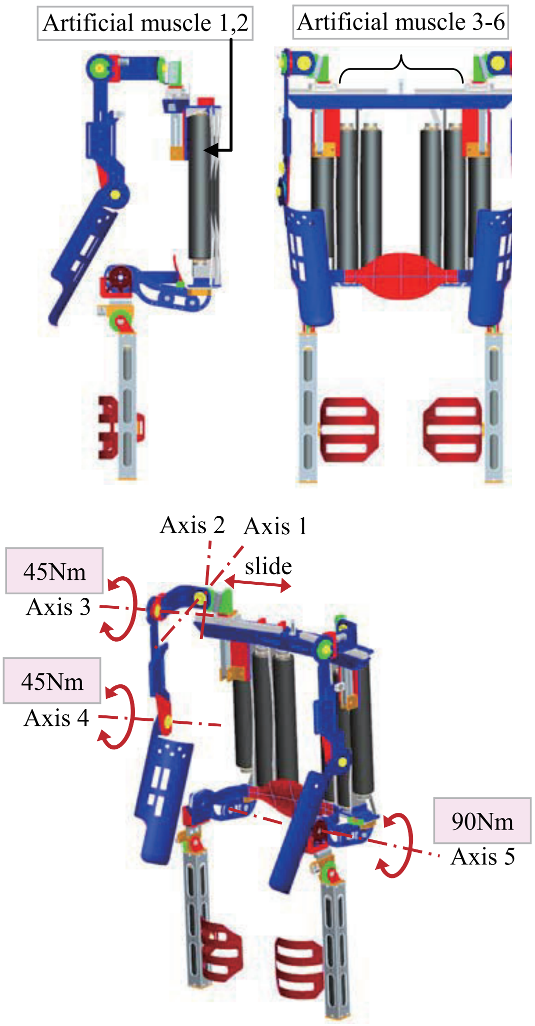


Fig. 5. Suit schematics.

Table 1. Muscle Suit Specifications.

Weight (kg)	9.2
Power source	Compressed air
DoF	Elbow 1 (Axis 4) Shoulder 4 (Axis 1 – 3+ slide) Waist 1 (Axis 5)
Support	Elbow 1 (Axis 4) Shoulder flexion (Axis 3) Forward tilt (Axis 5)
Support torque (Nm)	Elbow 45 (Axis 4) Shoulder flexion 45 (Axis 3) Forward tilt 90 (Axis 5)
Control	Feed forward

Analyzing factory personnel and caregiver movement, we concluded that supporting shoulder flexion (axis 3), elbow flexion (axis 4), and forward upper-body tilt (axis 5) is sufficient for carrying loads. Each axis has a pulley 50 mm in diameter. Connecting the wire from the McKibben artificial muscle to the pulley helps the axis rotate. Although how much torque the muscle suit should support remains unclear, we used support torque of 45 Nm

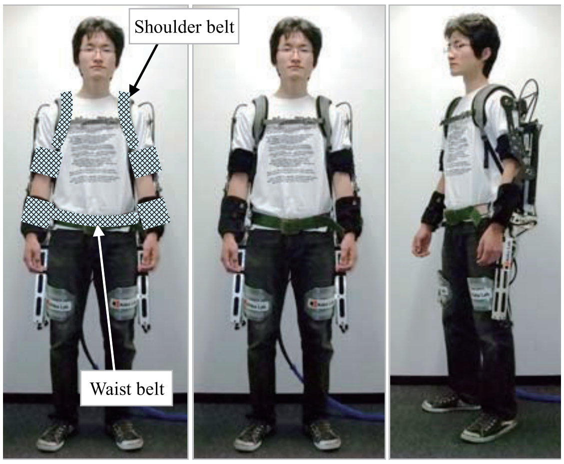


Fig. 6. Putting the muscle suit on.

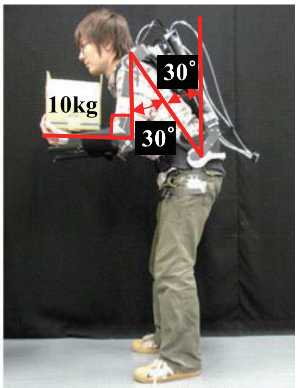


Fig. 7. Holding experiment.

Fig. 8. Factory trial.

for axes 3 and 4 and 90 Nm for axis 5 because the McKibben muscle produces 45 Nm per axis. Note that for the shoulder, the muscle suit supports axis 3 rotation although, since users can control other axes, pickup an object and folding an object in the arms are possible.

As shown in **Fig. 6**, a shoulder belt fits the muscle suit to the body and a waist belt supports the load on the muscle suit and the muscle suit's weight on the hips. Upper arm and forearm fit uses hook-and-loop fasteners.

Two university students taking part in load-holding experiments held a 10 kg load for 5 seconds in the posture in **Fig. 7**. Compressed air was manually supplied to McKibben artificial muscles so that the students did not feel they were using their own muscle strength.

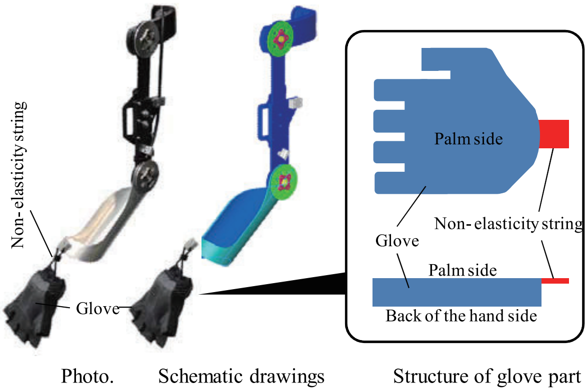


Fig. 9. New forearm structure with glove.

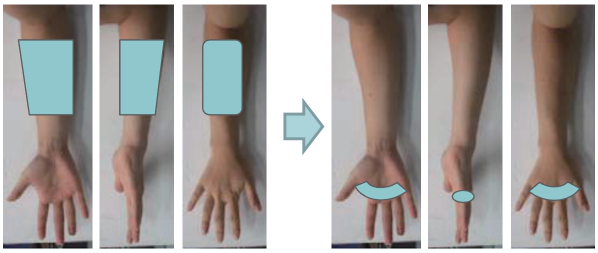


Fig. 10. Contact and pain change with new structure.

Integral ElectroMyoGraphy (IEMG) shows reduced muscle use. We found that the muscle suit reduced muscle use for the elbow, shoulder, and sacroiliac in all subjects. Concretely, muscle strength for the elbow and shoulder decreased 85% and for the sacroiliac 50% [35].

3. Suit Improvements

3.1. Mechanical Issues

Users most typically lift an object as shown in **Fig. 8**. Unlike load holding shown in **Fig. 7**, the muscle suit must support vertical movement for the arm. Pilot studies of this movement show that the user feels painful constriction in muscle suit frame and hook-and-loop fasteners at the forearm – in addition to feeling basically uncomfortable.

3.2. Forearm Frame with a Glove

To reduce constriction and discomfort, we propose the structure in **Fig. 9**. Lifting requires hand support. Using a glove connected by nonelastic string to the palm tip of the modified forearm frame reduced constriction pain at the forearm and supporting hand. As explained in **Fig. 10**, constricted area is drastically reduced. The new structure also generates adduction torque at the wrist engendering the feeling that support is comfortable in the user.

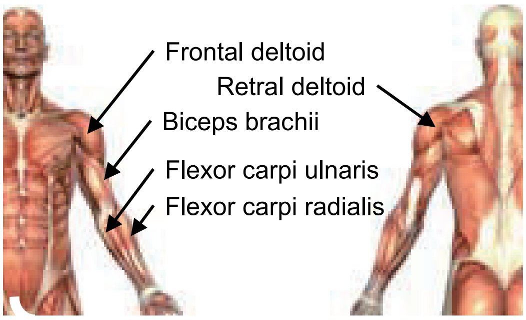
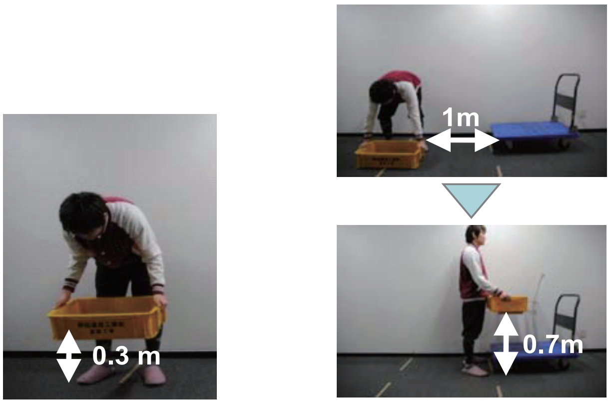


Fig. 11. Measurement sites.



(a) Holding (b) Lifting

Fig. 12. Evaluation experiments.

4. Suit Evaluation

4.1. Evaluation by IEMG

We evaluated the muscle suit's effectiveness by checking muscle force used in holding and lifting a load, which is measured by applying IEMG showing total muscle strength used during experiments.

Web-7000 (Nihon Kohden Co. Ltd., Japan) measures IEMG using the following specifications: sampling: 1 kHz; bandpass filter: 30-500 Hz; time constant: 0.01 s. IEMG measurement sites are shown in **Fig. 11**.

Ten university students taking part in load-holding experiments were required to hold a 20 kg load for 15 seconds keeping the posture in **Fig. 12(a)**. Compressed air is supplied manually to corresponding McKibben artificial muscles so users do not feel they are using their own muscles.

Figure 13 shows average IEMG for three trials obtained by 10 subjects with and without the muscle suit and the glove. We used EMG acquired during from 4 to 10 seconds in IEMG. To clarify muscle suit effects, we assigned 1 as the average IEMG without muscle suit use. t-test results are also shown.

We found that the muscle suit reduced muscle use for all subjects. Glove use also reduced muscle use, especially for the controlling finger – e.g., flexor carpi radialis, flexor carpi ulnaris, and biceps brachii. Just how much reduction is needed and effective using the muscle suit remains unclear, but subjects insisted it was much easier to maintain the posture with the muscle suit and glove.

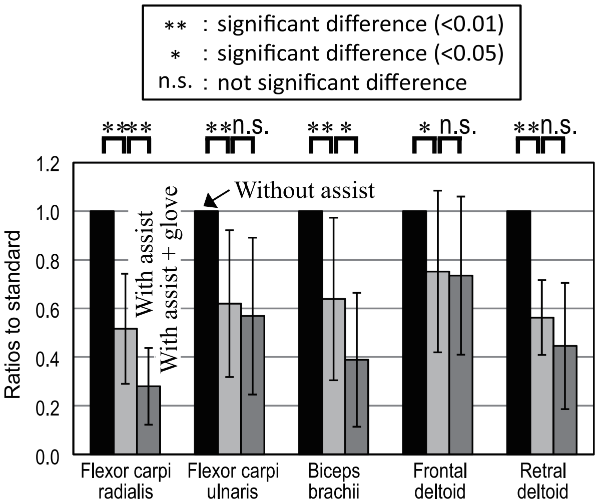


Fig. 13. Holding experiment results.

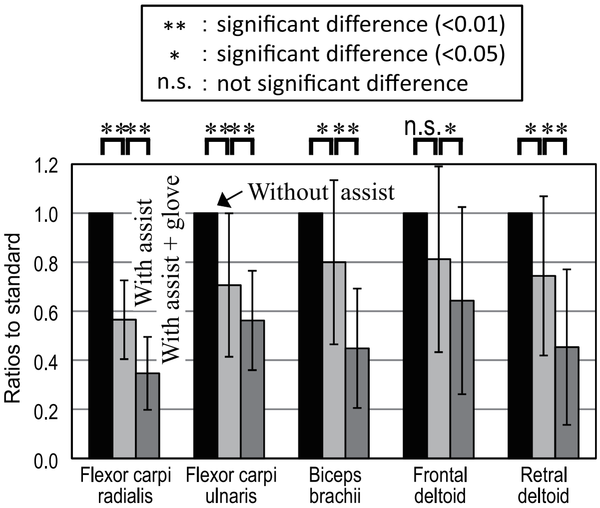


Fig. 14. Lifting experiment results.

Subjects, another 10 university students, were asked to lift a 20 kg load from the ground, move 1 m and leave it on a chair 0.7 m high, as shown in **Fig. 12(b)**. Because we use IEMG, measured time must be strictly controlled, so we had subjects do as follows:

1. Lift the load and stand upright – 3 seconds
2. Move 1m to the target position – 3 seconds
3. Put down the load – 1 second.

This took 7 seconds, during which we used EMG for IEMG, controlling lapsed time with a metronome. The McKibben artificial muscle was provided 0.5 MPa to support the shoulder and elbow. Subjects simply followed suit movement.

Figure 14 shows experiment results corresponding to **Fig. 13**. As in holding experiments, using the muscle suit and glove reduced muscle use for all subjects. The muscle suit and glove clearly supported lifting for the arms effectively.

4.2. Evaluation by Time Sequence Change in IEMG

Decreased muscle fatigue may be one of the most important factors showing the muscle suit's effects. Lactic acid is usually used to measure muscle fatigue, but this requires blood collection. Whereas we measured EMG to show muscle use with the time sequence change in EMG.

In additional load-holding experiments, subjects were asked to hold a 20 kg load for 60 seconds, as shown in **Fig. 12(a)**. **Fig. 15** shows the change in IEMG each 2 seconds during 60 seconds by one subject for each muscle and condition, with and without the muscle suit and with the muscle suit and glove. We found that change in IEMG were the smallest and seemed stable, as was also the case with the muscle suit and glove. Results for other subjects showed the same features. Because of smallest, constant value, we expect that subjects will not become tired easily if using the muscle suit and glove.

In additional load-lifting experiments, we ask subjects to repeat the load-lifting shown in **Fig. 12(b)** 30 times. **Fig. 16** shows the time sequence change in IEMG during 7 seconds per experiment obtained for one subject for each muscle and condition, with and without the muscle suit and with the muscle suit and glove. We found that for **(a)** flexor carpi radiali and **(c)** biceps brachii, the change in IEMG was the smallest and stablest, with similar results when subjects used the muscle suit and glove. Results from other subjects followed similar trends. Because dynamic movement requires a complex combination movement of muscles, we assume the change in IEMG in lifting experiments becomes unstable. Since the change in IEMG with the muscle suit and glove seemed stablest and smallest, however, we expect subjects not to become tired easily when using the muscle suit and glove.

4.3. Evaluation by Questionnaire

Since subjects come into physical contact with the muscle suit and are assisted by it, their subjective impression is very important so, after experiments, we had them complete questionnaires consisting of the following 5 questions:

Q1. Do you feel fatigued?

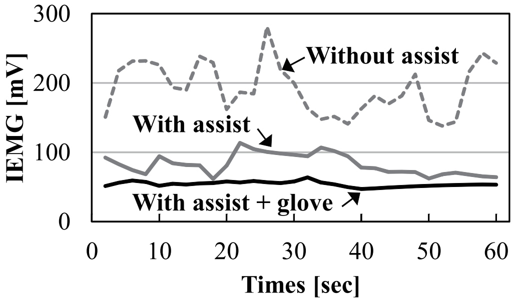
Q2. Could you feel supplementary strength provided by the muscle suit?

Q3. How was flexibility of movement when wearing the muscle suit? / Was it easy to move while wearing it?

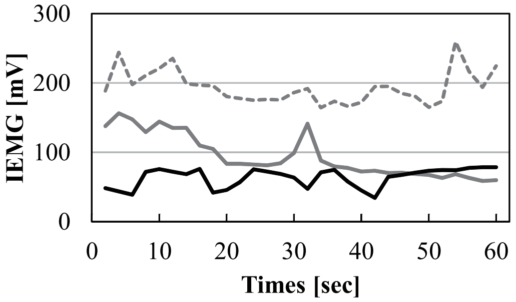
Q4. What did you feel like after putting the muscle suit on?

Q5. What was your impression about the dynamic assistance provided by the muscle suit?

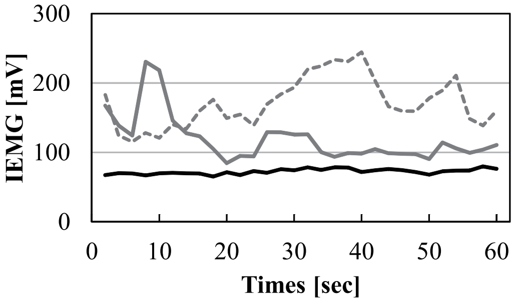
We ask subjects to score 0 to 5 – 5 being the best impression. For Q1, subjects had to compare states with and without the muscle suit and the state with the muscle suit and glove used together. Q2, 3, 4 and 5 compared use with and without the glove. "0" in Q2 is the state without wearing the muscle suit.



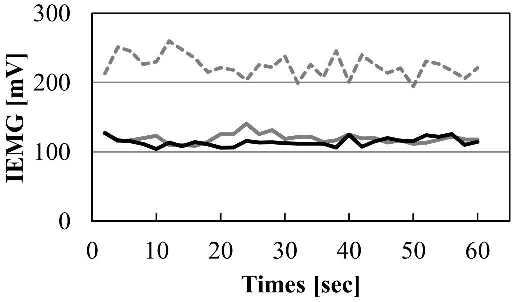
(a) Flexor carpi radialis



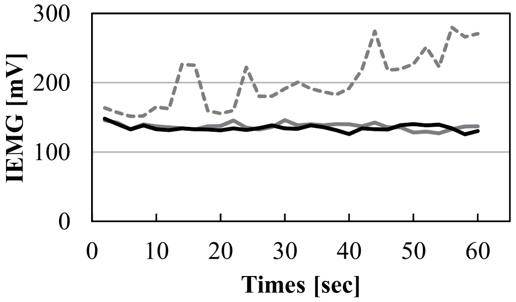
(b) Flexor carpi ulnaris



(c) Biceps brachii

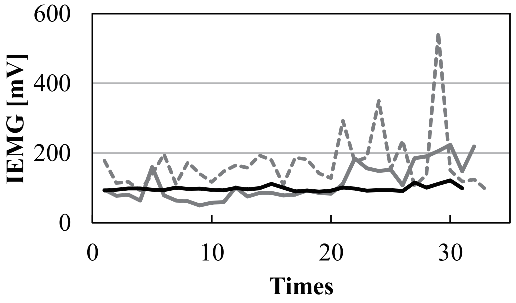


(d) Frontal deltoid

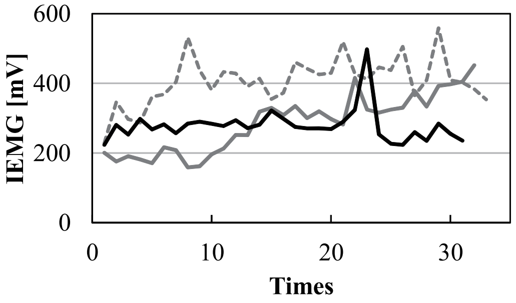


(e) Retral deltoid

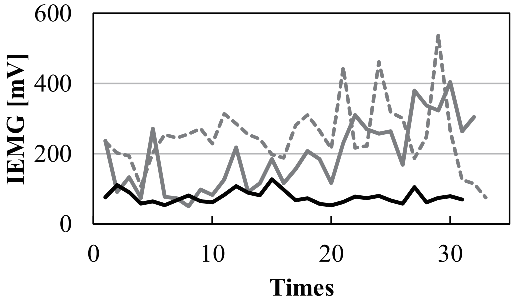
Fig. 15. Time sequence change in IEMG in holding experiments.



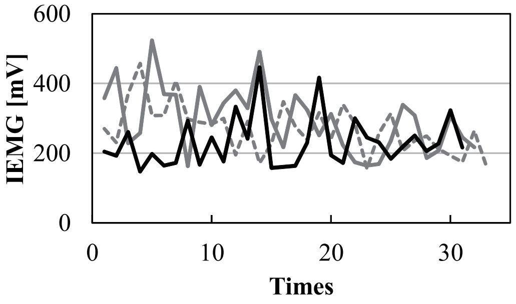
(a) Flexor carpi radialis



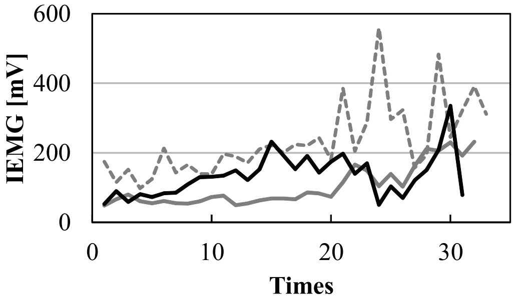
(b) Flexor carpi ulnaris



(c) Biceps brachii



(d) Frontal deltoid



(e) Retral deltoid

Fig. 16. Time sequence change in IEMG in lifting experiments.

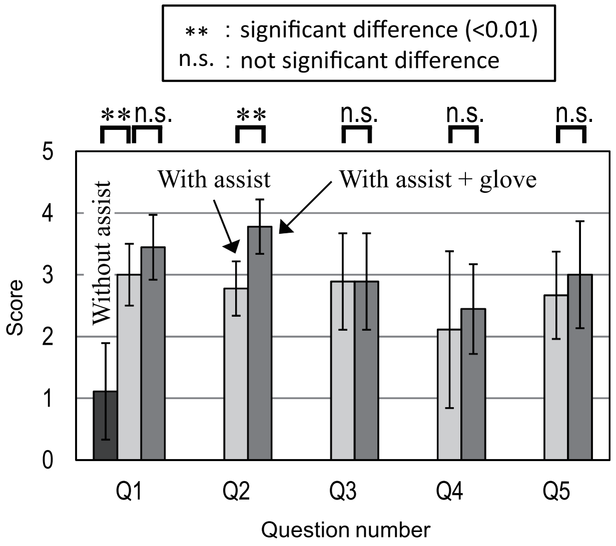


Fig. 17. Results from questionnaire.

Figure 17 shows average scores, standard deviation, and t-test results for from 10 subjects. Data from Q1 showed that subjects felt less fatigued wearing the muscle suit. Results from Q2 showed that subjects felt supplementary strength using the muscle suit. $t-$test results showed that subjects had the impression of more supplementary strength wearing the muscle suit with the glove than without the glove. Results for Q3 to Q5 approximating 2.5 (the midpoint) indicate we can say subjects do not feel great discomfort and / or a negative impression while wearing the muscle suit and glove.

5. Conclusions

Exoskeleton stories are largely anecdotal and, to the best of our knowledge, quantitative performance results have not been reported. The wearable muscle suit we are developing for direct and physical support has indicated quantitative evaluation results. Although augmentation devices basically work in concert with user movement, our muscle suit apply the following strategy "a human inside puts weight and / or movement on the muscle suit and / or movement of the muscle suit" to reduce muscle use required of the user.

For practical applications, we focused on lifting and improving the forearm structure so that the muscle suit assists vertical lifting. Load holding and lifting experiments showed the muscle suit's effectiveness in IEMG, time sequence change in IEMG, and questionnaire results. Note that, although the muscle suit is effective in assisting for a specific task, the muscle suit's weight – 9.2 kg – is additional load for the user. The user's decision on whether they will use the muscle suit or not should be based on the condition described above.

Issues remaining to be solved for practical use include the following:

1) The degree of support the muscle suit should provide

2) What the muscle suit should weigh

3) Muscle suit control

4) How the muscle suit is worn most effectively

5) Effects on users.

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