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Improvement and Quantitative Performance Estimation of the Back Support Muscle Suit

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Abstract—**We have been developing the wearable muscle suit for direct and physical motion supports. The use of the McKibben artificial muscle has opened the way to the introduction of "muscle suits" compact, lightweight, reliable, wearable "assist-bots" enabling manual worker to lift and carry weights. Since back pain is the most serious problem for manual worker, improvement of the back support muscle suit under the feasibility study and quantitative estimation are shown in this paper. The structure of the upper body frame, the method to attach to the body, and the axes addition were explained as for the improvement. In the experiments, we investigated quantitative performance results and efficiency of the back support muscle suit in terms of vertical lifting of heavy weights by employing integral electromyography (IEMG). The results indicated that the values of IEMG were reduced by about 40% by using the muscle suit.**

I. INTRODUCTION

Assistive technology for humans has about 50-year history. It is applied for augmenting the performance of healthy humans and also rehabilitation. For rehabilitation, many research works for both legs[1]–[10] and arm[11]–[13] are undertaken though, augmenting technologies are focused in this paper.

"Hardiman" (the "Human Augmentation Research and Development Investigation") is one of the most famous full-body augmenting device. It was an enormous powered machine (680 kg, 30 DOFs) by hydraulic transmission with components for the arms (including hands but without wrists) and legs of the wearer, developed in the late 1960s. Comparing to many other augmenting devices, Hardiman was supposed to drastically increase the strength of the wearer (approximately 25:1) [14]–[16]. The arm succeeded 25 times augmentation though, the lower limb components were never activated and the full-bodied device was never even powered up with a human inside.

In the middle 2000s, the Sarcos Research Corporation (Salt Lake City, UT) developed the same type of a augmenting device toward a "Wearable Energetically Autonomous Robot (WEAR)" under the DARPA EHPA (Exoskeletons for Human Performance Augmentation) program[17][18]. The Sarcos exoskeleton is carrying its own power supply employs rotary hydraulic actuators located directly on the powered joints. It demonstrated a number of impressive feats: structure supporting entire load of 84 kg, wearer standing on one leg while carrying another person on their back, walking at 5.8km/h while carrying 68 kg on the back and 23 kg on the arms, walking through 23 cm of mud, as well as twisting, squatting, and kneeling [19]. However, the design and performance has not been made public.

The full-body Hybrid Assistive Limb (HAL) has been developing as an assistive device that is targeted for both augmenting and rehabilitation at the University of Tsukuba, Japan [20]–[23]. HAL is actuated by a DC motor with harmonic drive placed directly on the joints. While there have been many demonstrations of the HAL being worn by a healthy operator, the performance of a physically challenged subject were not able to be found. Also the quantitative estimation of the upper and lower limb components are unclear.

These technologies mentioned above are typical one and thus, assistive devices are largely anecdotal though, there is a marked lack of published quantitative performance results.

We have been developing the wearable muscle suit[24]–[28] directly support motion for the upper body as shown in Fig.1. The purpose is to help users normally needing assistance to move unaided and it could also be useful in rehabilitation and in aiding manual workers. Use of the McKibben artificial muscle makes muscle suits lightweight and practical. Motivation to develop the muscle suits was originally to support the physically challenged, although practical use is still difficult from ethical and safety viewpoints. We then decided to apply them to manual workers for solving the problem of work-related disorders. The maturity of muscle suits is fairly high and more than 1000 visitors at the related exhibition tried it on so far. We then investigate the market research and have been developing the production design.

Figure 1. Muscle suits (Arm+back support, Back support)

Assistive or augmenting devices mentioned above basically work in concert with the operator's motion. Whereas, the muscle suit features "a wearer puts his or her weight and/or motion on muscle suits" strategy. Control then becomes very

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simple, i.e., give the motion pattern to muscle suits depending on the task by controlling values of compressed air supplied to each artificial muscle. The strategy gives good quantitative results with respect to keeping specific static posture with a load, i.e., up to 85% reduction of integral electromyogram (IEMG) were observed [28]. Since EMG is the well-known method for expressing muscular strength used, we apply IEMG for quantitative performance analysis.

The European Agency for Safety and Health at Work reports that Musculoskeletal Diseases account for 30% to 46% of all work-related sick leave[29]. Based on USA's National Institute for Occupational Safety and Health, 67% of nursing care personnel and 84% of automobile factory workers have back pain as work-related disorders [30]. When income loss due to work-related disorders and/or industrial accident compensation is considered, we can say that work-related disorder is a major and/or serious societal issue.

We therefore have been developing muscle suits for back support as well as the arm support ones. Cooperating with companies, product planning for back support has been undertaken so far. And then, based on the feasibility study (FS), improvement has been repeated. In this paper, crucial topics for amelioration are discussed and also quantitative estimation results are shown.

Section 2 describes the muscle suit configuration and Section 3 explains improvement of the muscle suit structure. Section 4 presents the effects of back support.

II. MUSCLE SUITS CONFIGURATION

A. McKibben-type artificial muscle

Because of its light weight, power-to-weight ratio, softness, waterproof finish, the McKibben-type artificial muscle was selected as an actuator [31]. The McKibben actuator was developed in the 1950s for artificial-limb research [32].

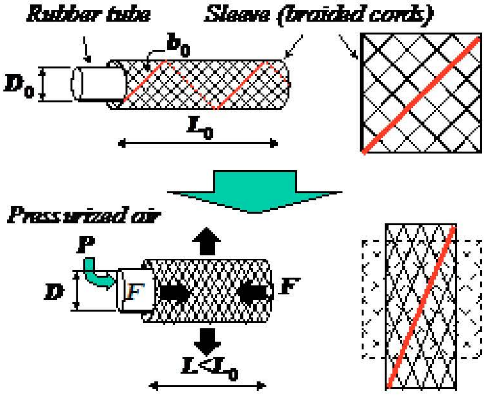
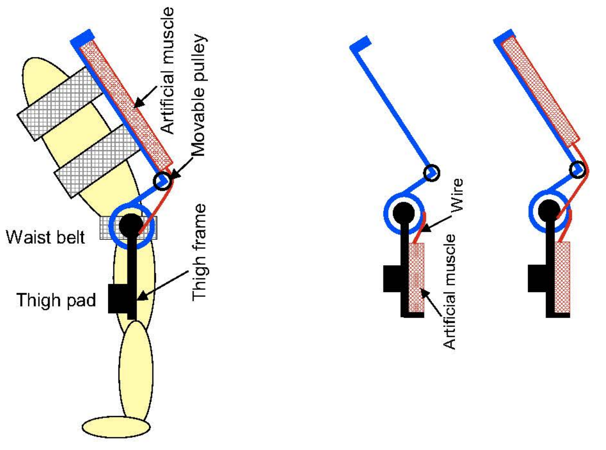


Figure 2. McKibben-type artificial muscle structure

The McKibben artificial muscle consists of an internal bladder surrounded by a braided code with flexible, nonexpandable threads attached at either end to fittings. As shown in Fig. 2, when the internal bladder is pressurized, inner surfaces is pushed against the external shell, expanding it. Due to the nonexpandability of threads in the braided code, the actuator is shortened and then produces a load if it is coupled to a mechanical load. This results in 35% contraction with no load and over 5% for a 150 kg load in case of 1.5 inch in diameter (D_0).

B. Operation Principle of The Back Support Muscle Suit

Forward incline of the upper body is supposed as the rotation of the upper body against the lower body around the hip joint. In Fig.3(a), the pulley shown as the blue outline circle rotates around one expressed by the black circle (fixed pulley). The blue outline circle pulley is connected to the back frame and one end of the actuator is mounted to the upper part of the back frame. The wire connected to the other end of the actuator is fixed at the fixed pulley through the pulley mounted at the back frame. The contractive force of the actuator then is converted to the turning force and the upper body is lifted up. The mechanism for mounting the fixed pulley to the body is one of the important issues. In this study, the waist belt and thigh frame connected to the fixed pulley are applied as described in Fig.3(a). Thigh pad is utilized for the reactive force against the upper body lifting. Depending on the environment, it is possible to mount the actuator at thigh part (Fig.3(b)), and also back+ thigh part (Fig.3(c)) if high torque is requested.



(a) (b) (c)

Figure 3. Principle for back support

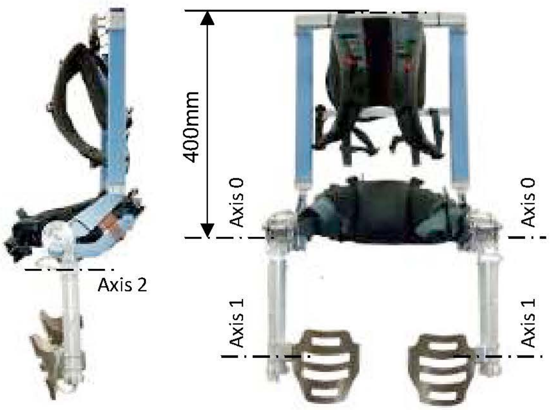


Figure 4. Principle for back support

It is said in Labor Standard Law of Japan that the limit of weight handled by humans must be less than 40% of his/her weight. The weight of 95% adult men in Japan is less than 76.6kg and then, since 40% equals to 30.6kg, we select the support power of the muscle suit as 30kg. As shown in Fig.4, because the length from axis 0 to the top of the muscle suit is 0.4m, we realize 120Nm by using 4 of the McKibben artificial muscle so that 30kg support is achieved. The maximum contraction power of the McKibben artificial muscle is 1500N and Pulley of 40mm in diameter is applied, we can expect 120Nm(120Nm=1500×4×0.02).

C. *System configuration*

The system configuration is shown in Fig.5. It consists of electric valve, pressure sensor, compressor, micro processor and sensor/switch. Instead of the compressor, it is available to use the tank. If 1.1 liter tank is applied with 19.6MPa, 150 times actuation is expected for one artificial muscle.

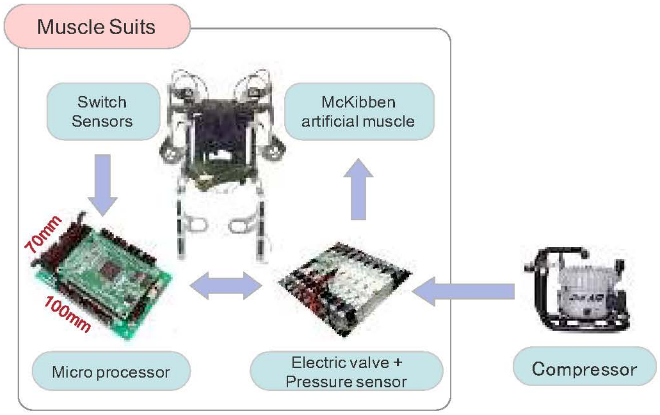


Figure 5. System configuration

III. IMPROVEMENT OF THE MUSCLE SUIT

Feasibility study (FS) has been investigating for a few year and many kinds of improvements have done. In this section, the major modification in terms of mechanical structure will be described. Note that, since the methodology in order to develop the assistive system which attaches directly to humans has not clearly existed so far, these improvements are based on subjective ideas and design of authors by the feedback from users.

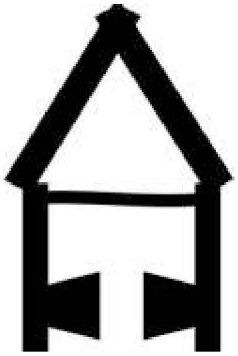


Figure 6. Concept of new structure

A. *Improvement of the upper body structure*

We worry about the load to thigh because of reactive force though, no one has negative response so far.

The issue obtained by FS was restriction of the upper body motion. In the real field, worker twists the body from side to side. The structure described in Fig.4 disturbs the motion, i.e., the top horizontal frame hits to the body, arms and elbow contact the vertical frame at the back part of the muscle suit, and so on. We then propose the structure shown in Fig.6. The upper body twists wider as the length from the hip to the shoulder becomes longer. The area of the muscle suit in Fig.6 becomes smaller as going to the upper part and then the movable rage of human upper body comes to wider to avoid its restriction. Fig.7 shows the new prototype based on the new concept. As the result, we confirm by hearing from users that the restriction is reduced in terms of the movable range of the upper body.

Figure 7. Concept of new structure

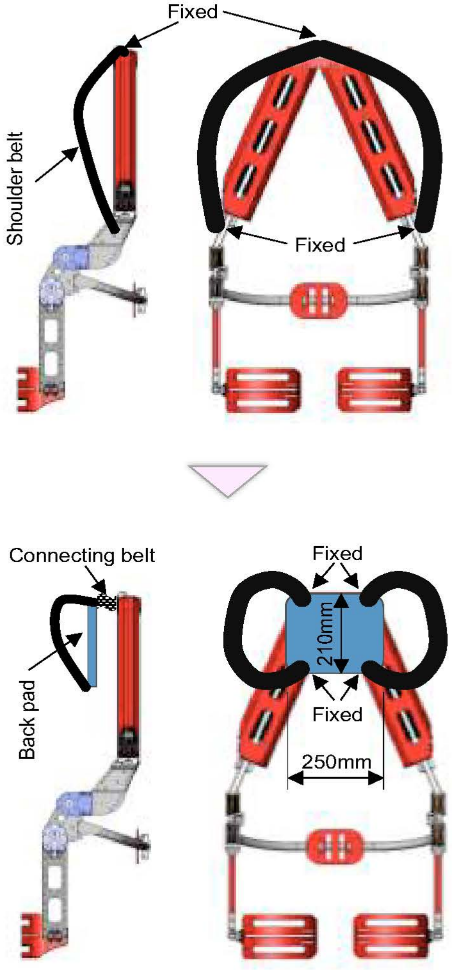


Figure 8. Wearing method to the upper body

B. Wearing method

As shown in Fig.8, the shoulder belt of the muscle suit mounts from the top to the back as the same as the backpack. The restriction as mentioned previous section is observed by this structure and wearing method. The back pad therefore is prepared independently and connects it to the top part of the muscle suit as displayed in Fig.8. In this structure, wearer connects to the muscle suit at a point and he/she can move freely. As a result, the feeling of restriction is reduced. Note that the size of the back pad is decided empirically.

In order to reduce the restriction of the upper body motion, the structure and wearing method have been improved as mentioned above. For evaluating the effect of improvement, we investigate how a movable range spread out. As described in Fig.9, subject sits on the chair and the lower part of body is fixed to the chair by the belt. Subjects can move freely for his/her upper body. By using 3D measurement device (OPTOTRAK Certus by NDI Co. Ltd.), movable range of the upper body is measured in terms of nothing to wear(free), wearing old muscle suit(old) and wearing one(new). Three healthy subjects are applied to the experiment and one result is expressed in Fig.10. We assign the 3D movable range of free as 100, and then the one for old and new with respect to each of three subjects are 43(old)/87(new)(shown in Fig.10), 45/89, and 38/86. We thus confirm that movable range becomes very close to the one for free.

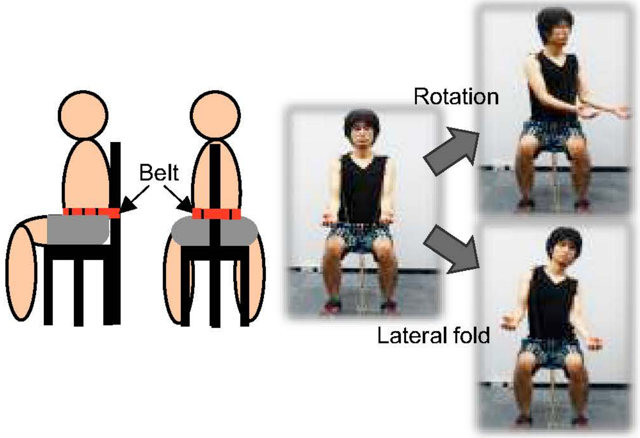


Figure 9. Experimental setup for measuring movable range

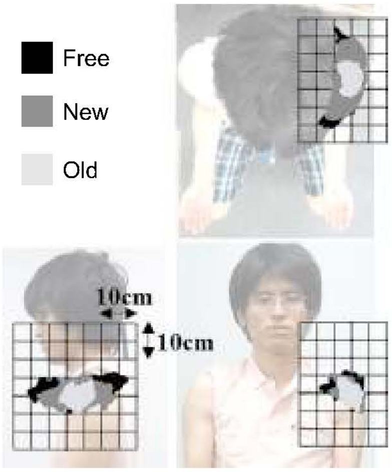


Figure 10. Movable range estimation

C. Addition of waist axis

At FS, we observed the muscle suit slid up on the body. When the upper body bends forward, the distance from the hip to the shoulder becomes longer. Since the muscle suit is connected to user by the shoulder belt, as a result, waist belt slides up. And then, assist force reduced in fact.

In case of human, when the upper body bends forward, the distance between the hip joint and the lower part of backbone mainly extends. In order to solve the issue mentioned previous paragraph, axes corresponding to the hip joint and the lower part of backbone are employed as described in Fig.11(Axis a and Axis b) so that elongation of the back is absorbed when bending the upper body. The size shown in Fig.11 is selected empirically though, we have had any trouble so far at FS.

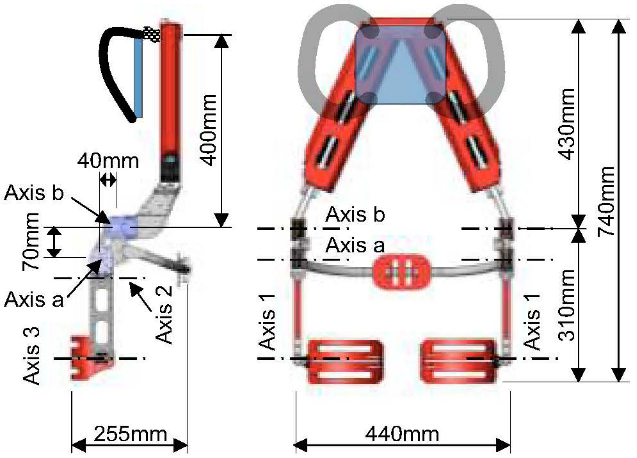


Figure 11. Improved structure

D. Addition of axis for thigh pad

In terms of the lower body structure of the muscle suit, Axis 1 and Axis 2 are prepared as displayed in Fig.11. At FS, we observed that the top edge and/or bottom one of the thigh pad cut into a thigh. This is because the muscle suit has different structure of human's one and the muscle suit slides on the body, and thigh and thigh frame become non-parallel. We then add the Axis 3 so that if thigh and thigh frame become non-parallel, whole area of thigh pad contacts to the surface of user's thigh. We confirm that no edge contact is observed.

Fig.11 shows the final improved model mentioned above. The weight is 5.5kg in total. The size is decided empirically though, we confirm the 30 university students (155cm – 178cm) can wear it and feel the assist force.

IV. QUANTITATIVE ESTIMATION OF THE MUSCLE SUIT

A. Experimental set up

All work site has tasks to carrying up heavy load. In this study, this operation is employed to estimate the effect of the muscle suit. As the typical operation in caring and physical distribution, the task shown in Fig.12 is applied.

In this study, 6mm in diameter tube and the electrical valve corresponding to the tube are used for supplying compressed air. Because of the specification of McKibben artificial muscle, 0.5MPa is used. We investigate the change in the value of compressed air after opening the electric valve and find that it takes about 1 second to reach 0.5MPa. Fig.13 shows images which subject wears the muscle suit. Switches are mounted to fingers of wearer and when he is ready to carry up the load, he pushes the switch and the compressed air supplies to artificial muscle. By the pilot study, we find it takes 2.5 seconds from forward bending to carry up the load. We then ask subject to exercise this motion so that the operation is undertaken in 2.5 seconds. We employ three healthy university students for this experiment.

Integral electromyography (IEMG) which shows total muscle power used during experiments, is applied to evaluate the muscle suit's effectiveness. Web-7000 (Nihon Kohden Co. Ltd., Japan) measures IEMG using the following specifications: sampling: 2 kHz; bandpass filter: 500 Hz; time constant: 0.01 s. The positions for measuring IEMG are shown in Fig. 14. We estimate IEMG obtained from 4 points with respect to right-left and up-down position differences.

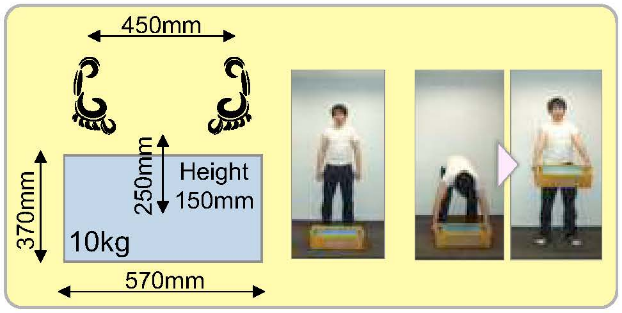


Figure 12. Experimental setting for lifting

Figure 13. Overview of muscle suit developed

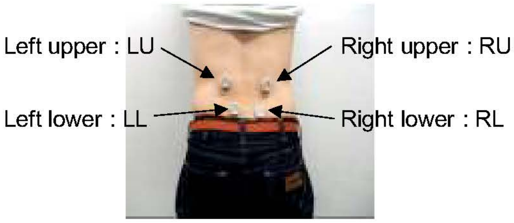


Figure 14. EMG measuring position

B. Evaluation

Fig.15 shows EMG obtained by a subject for RL with and without the muscle suit. We assigned 1 to the average value of IEMG without muscle suit use and Fig.16 displays the results.

We found that the muscle suit reduced about 40% muscle use for all subjects.

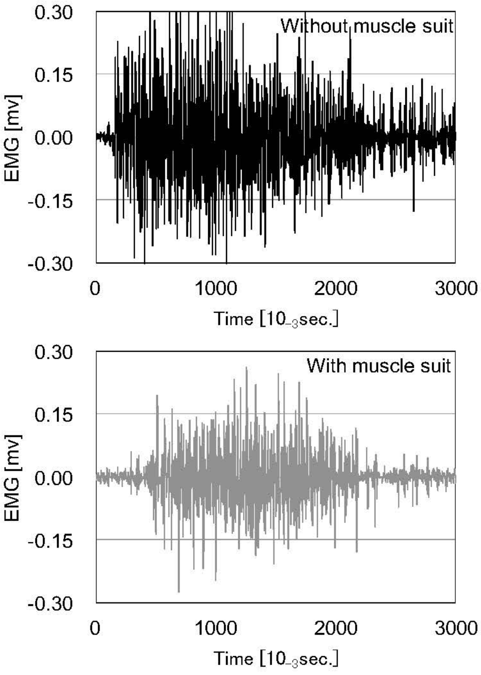


Figure 15. EMG measuring position

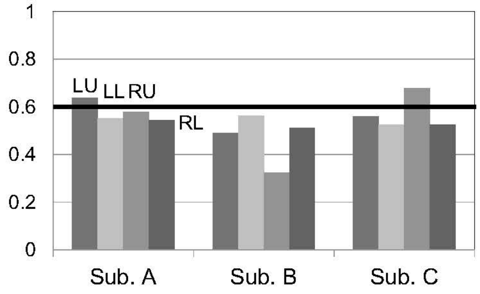


Figure 16. EMG measuring position

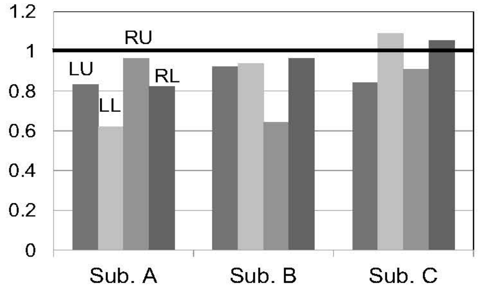


Figure 17. EMG measuring position

Note that EMG is observed when muscle is activated without any additional load. Then we can say that one method to estimate the muscle suit's effect is the comparison of IEMG obtained from operation with and without the load (10kg weight in this study) and the muscle suit.

Fig.17 shows the result. It describes the ratio of IEMG with load and the muscle suit when assigning 1 to IEMG without load and the muscle suit. We find that in most cases, values are less than 1 and it means that in spite of lifting the heavy load, if you use the muscle suit, muscle power used is the same as one obtained from the same motion without load.

V. CONCLUSION

The wearable muscle suit we have been developing directly and physically supports movement. Since back pain is the most serious problem for manual worker, improvement of the back support muscle suit under the feasibility study and quantitative estimation showed in this paper. The shape and structure of the upper body frame, the method to attach to the body, and the axes addition were explained as for the improvement.

In the experiments, quantitative performance estimation and efficiency of the back support muscle suit in terms of vertical lifting of heavy weights by employing integral electromyography (IEMG) have been investigated. The results indicated that the values of IEMG were reduced by about 40% by using the muscle suit. Also we find that in spite of lifting the heavy load, if you use the muscle suit, muscle power used is the same as one obtained from the same motion without load and the muscle suit.

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