Proceedings of the 2007 IEEE/RSJ International
Conference on Intelligent Robots and Systems
San Diego, CA, USA, Oct 29 - Nov 2, 2007

Development of Muscle Suit for Supporting Manual Worker

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Abstract— **A "muscle suit" that will provide muscular support for the paralyzed or those otherwise unable to move unaided is being developed as a wearable robot. The muscle suit consists of a mechanical armor-type frame and McKibben artificial muscle. Using a new link mechanism for the shoulder joint which consists of two half-circle links with four universal joints in total mounted at both ends of each link, all motion for the upper limb has been realized. Applying the muscle suit to non-healthy people such as elderly people and/or disable one requires very high-level safety and usability, from the practical point of view. We then in the first place for the practical use, apply the muscle suit to the manual worker. In this paper, we introduce how we can apply the muscle suit for a manual worker.**

I. INTRODUCTION

ASIMO and AIBO have been marketed for an aging society where children are decreasing in number. This calls attention to robot technology for supporting daily life in a human environment, including special environments such as those found in the field of medicine. Note that robot technologies consider use in the human living environment, although, few provide physical support or can directly provide human assistance. Kazerooni has been developing a robot so called Exoskeletons [1] to extend and/or augment human power for walking controlled by piston with a gas turbine. This is one of the wearable robot though, it is not for supporting human daily life (for army in fact). HAL[2] has been developing to assist walking by attaching orthosis to human body which is controlled by motor. It is required size adjustment to wearer and therefore custom-made is necessary. Since only one subject is using HAL for demonstration, no one knows it really works or not. Moreover, it is crucial to have a structure for not to have a falling for practical application. Another power assist suit [3] and power assist apparatus called HALL [4] have been specifically developed as wearable robots. These systems have the potential for aiding a caregiver, but because of their heavy metal frames, they are difficult to use in daily life. An exoskeleton to assist elbow and forearm motion especially for physically weak persons has been also constructed [5] though, it has the same drawback.

Whereas we have been developing a muscle suit [6]-[9], a wearable robot that directly and physically supports human movement. The purpose of the muscle suit is to help a patient, who normally needs assistance, move unaided. It could also prove useful to rehabilitation and a manual worker. The patient will be able to willfully control his movement with the muscle suit, which provides both muscular and emotional support. In addition, use of McKibben artificial muscle allow the muscle suit to be lightweight, making it realistic to use in daily life.

Wearable system and robots normally consist of pole-like metal frames and joints, and they are attached to human body by band and/or hook-and-loop fastener. A wearer has a pain if the position of joint is not precise and feels heavy load from attached parts. Whereas, since the muscle suit does not have to attach to the wearer and the wearer is given load from inner surface of the muscle suit, the wearer does not feel a pin point pain. Moreover the muscle suit is manufactured a little bigger than human limb diameter and then the wearer can move inside of the muscle suit. These features make the muscle suit be free from precise adjustment to the wearer, i.e. flexible in size adjustment.

The motivation for developing muscle suit is for supporting non-healthy people, i.e., elderly and handicapped though, when we think of practical use of muscle suit, from ethical and also safety point of view, it will be hard to apply it to them from the early stage. We therefore decide to apply muscle suit to a manual worker.

In this paper, Section II describes the concept of the muscle suit, and Section III explains configuration of muscle suit and verifies its feasibility by testing a prototype system, focusing on its physical support and availability. In this process, unsolved issues emerge. To overcome them, an armor-type muscle suit proposed with special shoulder links in order to realize all arm motion. Section IV illustrates practical task for supporting manual worker and how to improve the structure of muscle suit for it. Section V describes estimation of efficiency of muscle suit for undertaking the task.

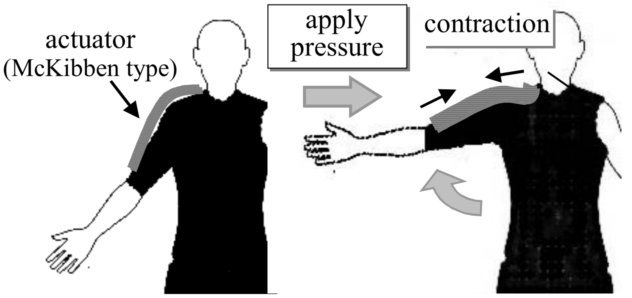

Fig. 1 Principle of operation of muscle suit.

Manuscript received March 28, 2007

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II. BASIC CONCEPT OF MUSCLE SUIT

The muscle suit is a wearable muscular support apparatus that is capable of moving a human, with the purpose of providing human physical support in a wide variety of applications. The basic concept is illustrated in Fig. 1. The McKibben artificial muscle was chosen for its light weight, flexibility, and large output. As shown in the figure, both ends of an actuator are sewn into a garment. Upon receipt of pressurized air, the actuator contracts and the garment pulls, lifting the wearer's arm.

The muscle suit is a new robot technology designed as a muscular support apparatus, which aids the wearer's movement by simply wearing the garment like a suit. Unlike conventional general robots, the joints are not directly rotated with actuators. Instead, actuators resemble muscles, which simulates the smooth and flexible characteristics of human movement.

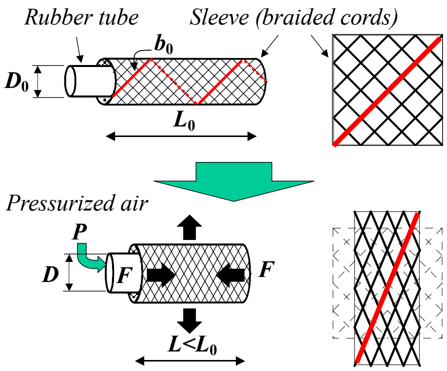


Fig. 2 Structure of McKibben artificial muscle

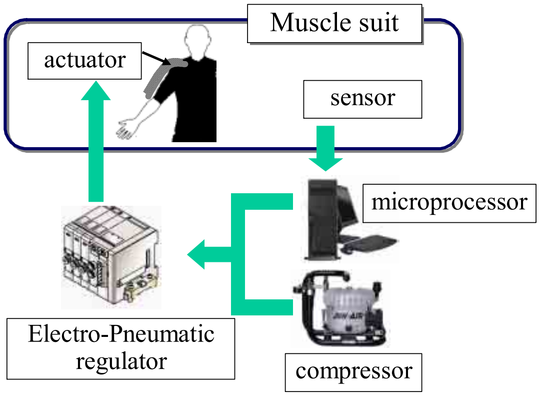


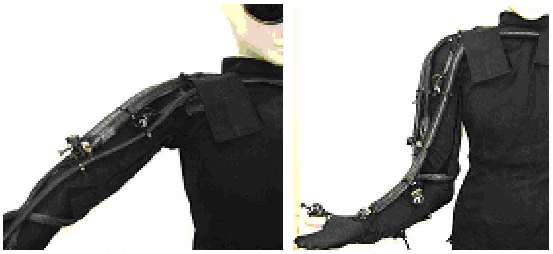
Fig. 3 System configuration

III. CONFIGURATION OF MUSCLE SUIT

A. McKibben artificial muscle

This section provides a description of the McKibben artificial muscle. The McKibben-type actuator was developed in the 1950s and 1960s for artificial limb research [10]. It is small, lightweight, simple, soft, flexible, and has no stiction [11]. Power-to-weight ratio is vastly outperforming.

The McKibben-type actuator consists of an internal bladder surrounded by a braided mesh shell (with flexible yet non-extensible threads) that is attached at either end to fittings. As shown in Fig. 2, when the internal bladder is pressurized, the highly pressurized air pushes against its inner surface and against the external shell, tending to increase its volume. Due to the non-extensibility of the threads in the braided mesh shell, the actuator shortens according to its volume increase and/or produces a load if it is coupled to a mechanical load. About 35% contraction can be expected with no load, and more than 20% for 20 kg load.



Abduction Bending an elbow

Fig. 4 Motion examples by using a life-size doll.

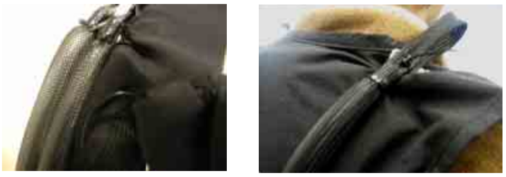


Fig. 5 Examples of slippage and slack

B. System configuration

The system requires a compressor, a microprocessor, and an electropneumatic regulator as shown in Fig.3. The electropneumatic regulator controls the compressed air output according to an analog signal from the microprocessor.

The size and weight of an electropneumatic regulator are 22x52x58.5[mm] and 181[g]. H8 microprosessor (50x70) is employed. The total current is less than 30[mA] and battery is usable. Although a McKibben artificial muscle is required an electropneumatic regulator, the system is not large and heavy even with 4kg-weight muscle suit. It may say it is movable. Whereas the system is required compressed air from the compressor which is difficult to carry. However the factory has pipe arrangement for compressed air and we can use it for muscle suit by connecting the tube to pipe arrangement. Also for a house, we are supposed to prepare the tube for supplying compressed air from ceiling. It is said that muscle suit thus is movable and workable where a wearer wants to work without compressor.

C. Issue of basic concept of muscle suit

A doll is used (for bandage exercise made by Kyoto Science Co., Ltd., 40 cm wide, 25 cm deep, 150 cm high, and weighing about 15 kg) to determine whether a person wearing the muscle suit would be able to move. In this experiment, the motion of the arm was checked. The motion of the entire body, including walking, will be examined in the future.

Fig.4 shows abduction motion and bending the elbow as examples. We experimentally determined the length and mounting position of an actuator and other parameters. From this experiment, we confirmed that human could wear the muscle suit for implementation of motion corresponding to the respective degrees of freedom.

Meanwhile, we find limitation of the muscle suit's range of motion. For example, as shown in Fig.4, the muscle suit can lift up the arm (abduction) up to about 40 degrees, and this seems to be the limit. The limitation is also implied the limitation of basic concept of the muscle suit as well. Muscles of mammals are attached directly to bones, giving mammals a very wide range of motion, largely because the distance between a joint and one end of a muscle is relatively short. Because the muscle suit is essentially a garment worn on the skin covering the bones, the distance between a joint and one end of an actuator must be greater than the distance between a joint and an end of a muscle in a mammal. From this point of view, it will be very difficult for a muscle suit to realize a human's full range of motion.

Also, slippage and slack of wear in the displacement of the muscle suit will cause losses; i.e., the full stroke of an actuator's contraction is not directly conveyed to the muscle suit. This concept is illustrated in Fig. 5. Moreover, in the case of the muscle suit, since human bones and skeleton are used as a pole, bones and joints are forced to withstand load produced by actuators. Thus, the muscle suit may apply a large load to the wearer's joints and bones.

D. Concept of Armor-type Muscle Suit

To overcome these issues, we proposed application of the armor structure, i.e., use of the mechanical joint and cylindrical frame connected by joints. Fig. 6 shows the degree of freedom which is necessary for all seven motions (Flexion, Abduction, Inner rotation, Extension, Adduction, Outer rotation, and Flexion of Cubital Joint) for the upper limb. Fig. 7 describes the overview of new structure muscle suit. Table I shows combination of actuators required to realize each motion. The total weight is 4 kg. It is not clear 4kg is heavy or not. The estimation of the weight will investigate in near future though, less than 3kg will be expected if we use magnesium and/or FRP.

Shoulder joint has to achieve three DOF, i.e. 1, 3, and 4 shown in Fig.6. Let here briefly discuss how new structure works. Fig.8 depicts a new shoulder joint mechanism which consists of two half-circle links and four universal joints mounted at both ends of each link. The mechanism is similar to ref.[12] and Cybernetic Shoulder(Fig.9)[13] which is the same concept as ref.[12]. As shown in Fig.9, Cybernetic Shoulder consists of three half-circle links located at each 120 degrees and by controlling center axis, motion which is similar to human's one is realized. While in case of the muscle suit, two half-circle links are mounted at each 180 degrees along the outer half of cylindrical surface so as to keep room for wearer.

The size of half-circle link is decided in consideration of the center of rotation and wide open space for wearer. Fig.10 shows the trajectory of motion in coronal plane. Motion in sagittal plane is realized as the same manner. It can say that wide movable range is achieved by this mechanism.

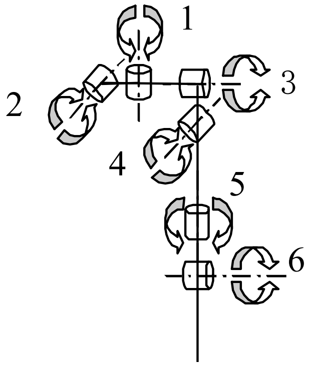


Fig. 6 Degree of freedom required for the all upper limb motions.

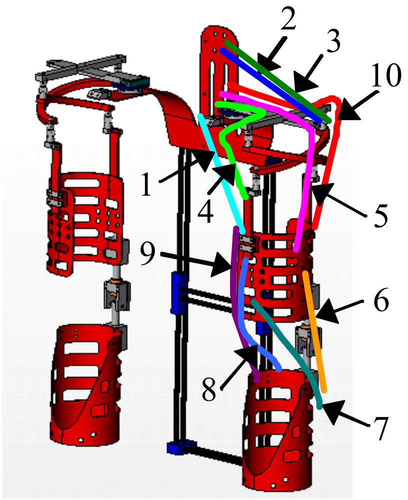


Fig. 7 Structure of new muscle suit

TABLE I. COMBINATION OF ACTUATORS FOR EACH MOTION

	Motions	Actuators
Shoulder Joint	Flexion	2, 3, 4
	Extension	10
	Abduction	2, 3, 5
	Addcution	1, 4
	Outer rotation	8
	Inner rotation	7
Cubital Joint	Flexion	6, 7, 8, 9

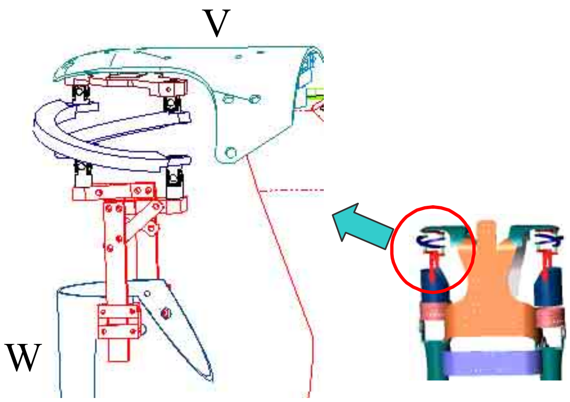


Fig. 8 Structure of a new shoulder mechanism

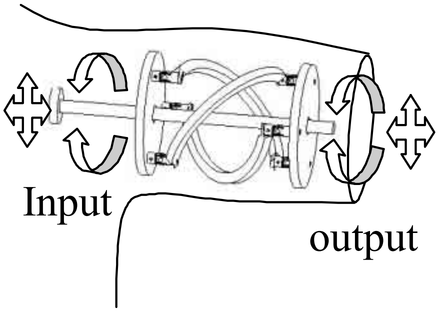


Fig. 9 Mechanism of Cybernetic Shoulder

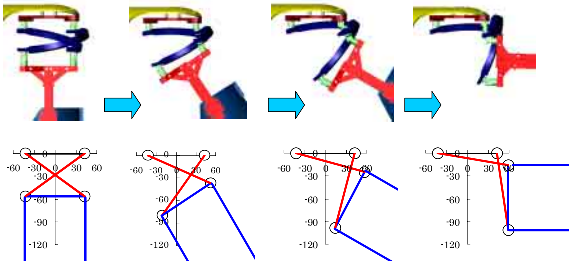


Fig. 10 Motion of new shoulder mechanism in coronal plane

IV. MUSCLE SUIT FOR SUPPORTING MANUAL WORKER

A. Task

We were asked to support a specific task as shown in Fig.11 from heavy-equipment manufacturer by using muscle suit. In this case, a worker has to uplift 10-20kg metal plate above his head by left arm and screws it to body of the power shovel from beneath by right hand. A worker has to endure heavy burden though, because of very narrow space, no machine is applicable for it. It may say that the only solution is wearable-type power assist system.

In order to realize power assist system, we improve muscle suit as follows in terms of mechanical structure and fixation to the body.

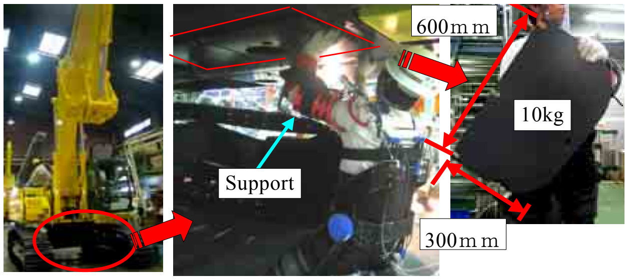


Fig. 11 One of required task for muscle suit

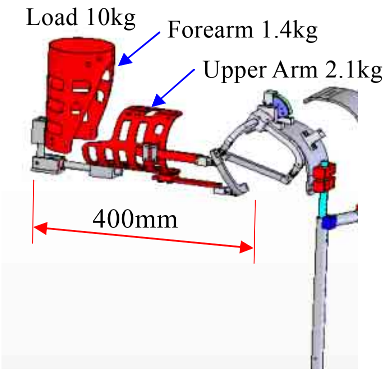


Fig. 12 Posture and load to be realized

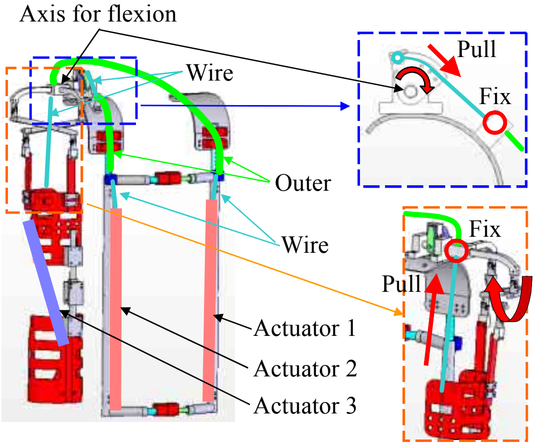


Fig. 13 Improved structure and actuator layout

B. Mechanical structure

Fig.12 depicts posture and load we want to realize by muscle suit for power assistance. Weights for forearm and upper arm described in the figure are the average of adult male. 90-degrees flexion of shoulder joint and 90-degrees flexion of cubital joint are required.

In order to realize stable and effective power transmission, we modify mechanical structure and actuator layout as shown in Fig.13. We employ inner wire so that we can mount actuators in a straight line at back part of muscle suit and actuators can transmit power anywhere through outer wire. For flexion motion of shoulder joint, axis for flexion is rotated by actuator 2 and upper arm is uplifted by actuator 1.

Actuator 3 is used for flexion of cubital joint. The total weight is 3.5kg in this model.

C. *Fixation to the body*

In case of muscle suit we have developed so far, the shoulder of wearer suffers from load, i.e. weight of muscle suit (3.5kg) and additional weight and/or load (13.5kg in case of Fig.12). We can say that it is impossible to use muscle suit for a long time. Whereas alpinist carries over 80kg weight on his back. They use a special rucksack with mechanical frame and basically support load at lower back. We then change the back-part structure of muscle suit. By using urethane board at lower back and belts as shown in Fig.14, muscle suit is fixed to the body. In this case, load is supported at lower back via urethane board and there is room between shoulder part of muscle suit and one of wearer.

Moreover, for size adjustment, width and height of back part are changeable by varying frame length manually as shown in Fig.15.

We find that it takes 30 sec. for wearing muscle suit. Although we do not know an ideal time for wearing, we think 30 sec. is bearable time.

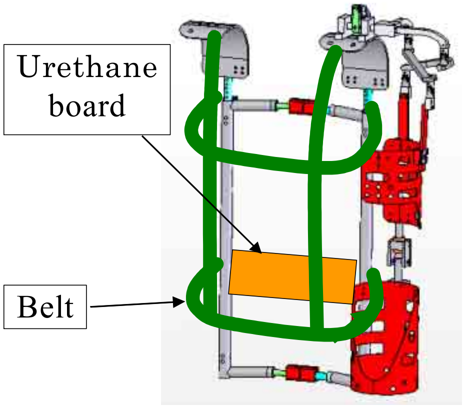


Fig. 14 New structure for supporting load at lower back

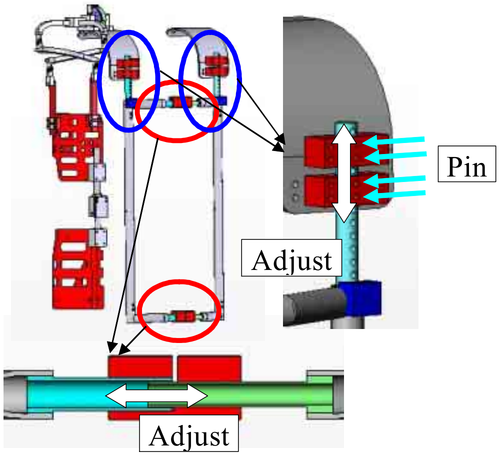


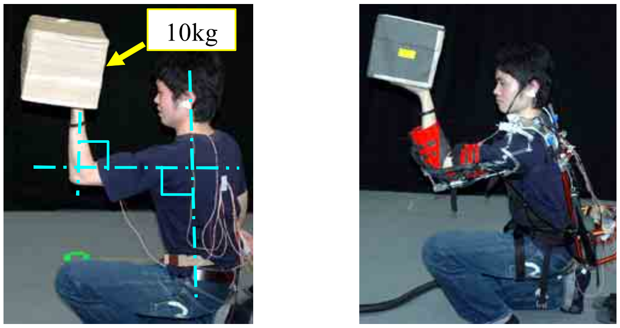
Fig. 15 Size adjustment mechanism

V. ESTIMATION OF MUSCLE SUIT

A. *Experimental set up*

5 male university students are employed for the experiment. The experiment as shown in Fig.16 is undertaken under the same condition mentioned in IV A. In the experiment, muscle power is measured by applying integral electromyogram (IEMG) which shows total amount of muscle power used during the task.

The experiment is repeated 4 times with and without muscle suit, and average of IEMG is calculated. We apply 0.5MPa to all actuators so that wearer can keep the posture shown in Fig.16 for 5 seconds.



Without muscle suit With muscle suit

Fig. 16 Overview for experimental

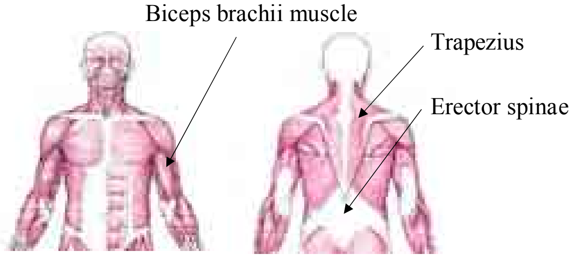


Fig. 17 Positions for measuring IEMG

B. *Measurement of IEMG*

WEB-5500 from NIHON KOIUDEN Co. Ltd. is employed for measuring IEMG. Bipolar lead method is used, distance between electrodes is 5cm and earlap is applied as body earth. Specification for measurement is as follows; sampling rate: 2kHz, band pass filter: 15-500Hz, time constant: 0.01sec. Three positions for measuring IEMG are shown in Fig.17.

C. *Experimental results*

Fig.18 depicts average values of IEMG for 4 trials with and without muscle suit for 5 subjects. Elbow describes IEMG for Biceps brachii muscle, shoulder for Trapezius muscle, waist for Erector spinae. In this figure, we assigned 1 to average value of IEMG without muscle suit.

We find that muscle suit succeeds in reduction of muscle power for all subjects in terms of elbow and shoulder. From t-test result, 5% significant level is acquired and then we can

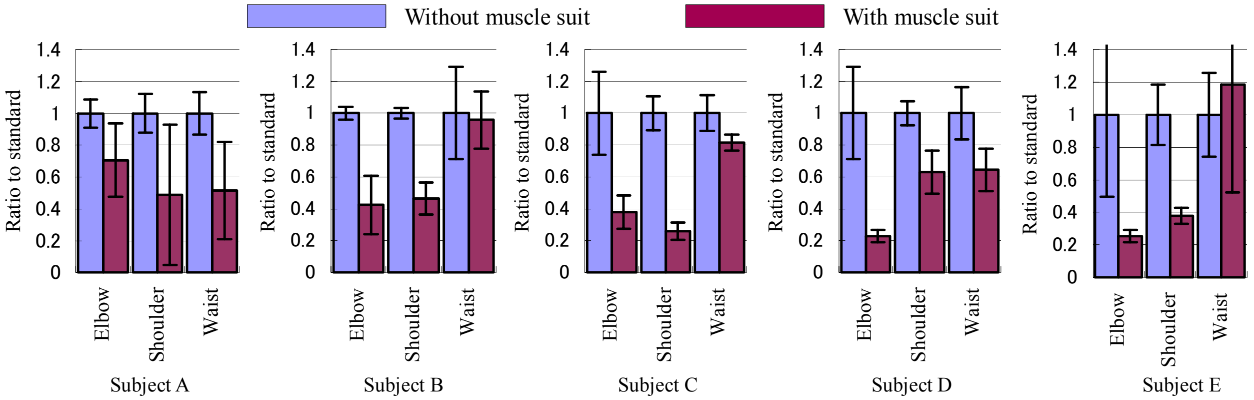


Fig.18 IEMG measurement results

conclude that muscle suit is efficient for supporting heavy load. Note that muscle suit directly supports elbow and shoulder, and does not assist waist. Whereas muscle power required for waist is decreased with respect to 4 subjects out of 5. It is a kind of side effect and we do not exactly know the reason. It might be the reason that because of power assist by muscle suit, wearer can hold a good posture.

VI. CONCLUSION

The muscle suit which is capable of moving a human, with the purpose of providing human physical support in a wide variety of applications is presented. Although the purpose for developing muscle suit is for supporting non-healthy people, when we think of practical use of muscle suit, from ethical and also safety point of view, it will be hard to apply to them, i.e., elderly and handicapped. We therefore decide to apply muscle suit for a manual worker.

Uplifting 10kg weight above head is undertaken by applying muscle suit and muscle power used is measured by integral electromyogram (IEMG). We find that muscle suit succeeds in reduction of muscle power for all 5 subjects. Moreover, muscle suit directly supports only elbow and shoulder though, load of erector spinae muscle which is used for supporting upper body posture is decreased.

We have been developing commercial products and trying to find practical applications for muscle suit.

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