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Development of Muscle Suit for Upper Limb

H. Kobayashi
Dept. of Mechanical Engineering
Science University of Tokyo
1-3 Kagurazaka, Shinjuku, Tokyo 162-8601, JAPAN
hiroshi@kobalab.com

K. Hiramatsu
Muscle Care Project
Hitachi Medical Corporation
1-2-10 Uchikanda, Chiyoda, Tokyo 101-0047, JAPAN

***Abstract*—We have been developing a "muscle suit" that provides muscular support to the paralyzed or those otherwise unable to move unaided, as well as to manual workers. The muscle suit is a garment without a metal frame and uses a McKibben actuator driven by compressed air. Because actuators are sewn into the garment, no metal frame is needed, making the muscle suit very light and cheap. With the muscle suit, the patient can willfully control his or her movement. The muscle suit is very helpful for both muscular and emotional support. In this paper, we propose an armor-type muscle suit in order to overcome issues of a prototype system and then show how abduction motion which we believe is the most difficult motion for the upper body, is realized.**

Keywords- Muscle suit, Wearable robot, Muscular support apparatus, McKibben artificial muscle, Abduction motion

I. Introduction

Honda ASIMO and Sony 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. According to their specific applications, these robots are classified as medical, nursing care, personal, humanoid, and coexistence robots. Note that robot technologies consider use in the human living environment recently, although, few provide physical support or can directly provide human assistance. We then have proposed a muscle suit [1][2] as a wearable robot for physically and directly supporting human movement. Kazerooni have been developing a robot so called extender [3] to extend and/or augment human power in terms of arm by attaching the huge robot arm to human one. This is one of the wearable robot though, it is not for supporting human daily life. Power assist suit [4] and power assist apparatus called HALL [5] have been developing as the wearable robot. These are improving for caregiver, very heavy because of metal frame, and it probably is difficult to use them in daily life. While the muscle suit is made for the patient in need of nursing and/or those unable to move unaided, as well as to manual worker. With the muscle suit, the patient can willfully control his or her movement. The muscle suit is very helpful for both muscular and emotional support. Also the muscle suit is light because of no metal frame and this makes possible to use in daily life.

In this paper, we describe the concept of the muscle suit and verify its feasibility by testing a prototype system. Although the muscle suit works to some degree, we find that use of a garment severely restricts the range of motion in comparison with the human's range of motion. To overcome this limitation, we propose an armor structure using a soft frame (no metal). Among movements of the upper limb, abduction is probably the most difficult to realize, because of weight and range of motion. We try to realize abduction by using the armor-type muscle suit.

Chapter II describes the concept of the muscle suit, and Chapter III verifies its feasibility by testing a prototype system, focusing on its physical support and availability. In this process, unsolved issues emerge. To overcome them, Chapter IV describes an armor-type muscle suit and investigates its capability by geometric analysis and an experiment.

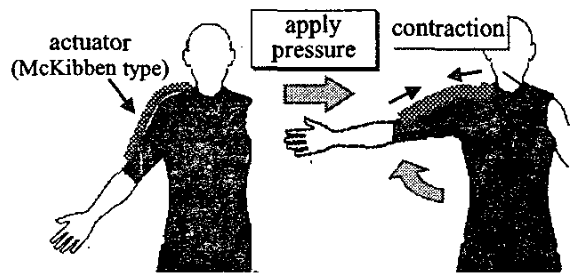


Figure 1. Principle of operation of muscle suit.

II. Concept of Muscle Suit

We discuss a wearable muscular support apparatus (muscle suit) capable of moving humans, focusing on human physical support and wide applicability. The basic concept is illustrated in Fig. 1. We select McKibben artificial muscle, by virtue of its light weight, flexibility, and large output. As shown in this figure, both ends of an actuator are sewn on a garment. Upon receipt of pressurized air, the actuator contracts and the garment is pulled, lifting the wearer's arm.

Muscle suit robot technology is applied directly to supporting human motion and designed to be available to many people. The muscle suit has the following features:

- Enables a person wearing the suit to realize any kind of motion.
- Uses a pneumatic actuator (Chapter III), called a McKibben artificial muscle, which is lightweight, flexible, and has large output.
- Provides lightweight physical support sufficient for muscular strength without use of a metal frame, by virtue of the actuator being sewn in the suit.

- Enables independent movement by the wearer, enhancing independence and providing encouragement.

The muscle suit is a new robot technology for a muscular support apparatus that allows the wearer to move simply by wearing it. Unlike conventional general robots, it does not rotate the joints directly with actuators, and it is expected to move in a smooth and flexible manner resembling human movement, via actuators resembling muscles. Since the muscle suit is applied directly to a human, it is based on a concept different from that underpinning conventional robot technology.

III. Prototype of Muscle Suit

A. McKibben artificial muscle

Let's briefly describe McKibben artificial muscle. The McKibben-type actuator was developed in the 1950s and 1960s for artificial limb research [6]. It is small, lightweight, simple, soft, flexible, and has no stiction [7]. 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.

Fig.3 shows the relationship between pressure and contraction rate for various loads. The results show that about 35% contraction can be expected with no load, and more than 20% for a load of 20 kgf.

As we described above, the McKibben-type actuator is very soft and flexible. The muscle suit uses these features effectively. That is to say, we arrange actuators that conform with the curved surface of the wearer's body.

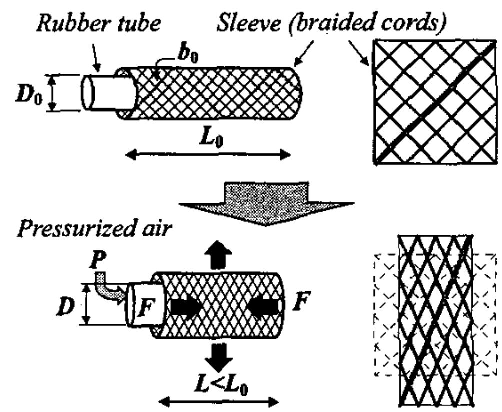


Figure 2. Structure of McKibben artificial muscle

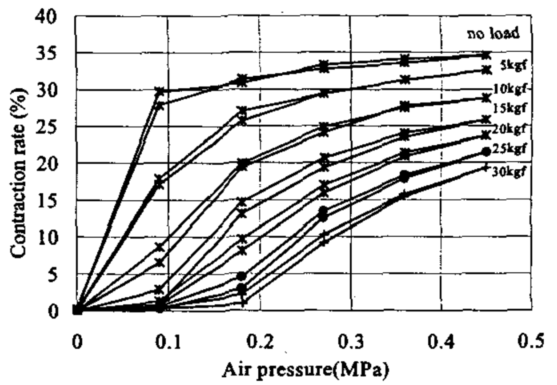
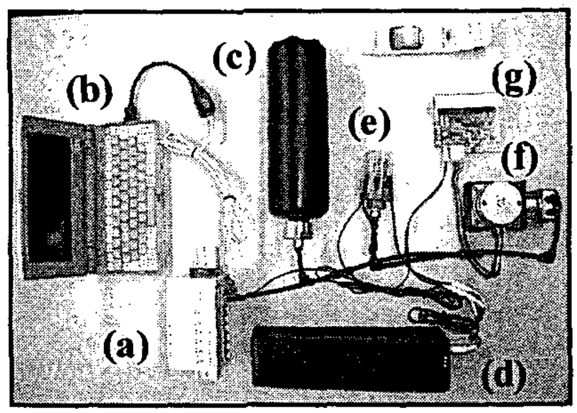


Figure 3. Relationship between relative air pressure, contraction rate, and load



(a) Electropneumatic regulator: 770g (b) PC: 750g
(c) Tank: 880g (d) Battery: 660g
(e) Pressure switch: 280g (f) Compressor: 1200g
(g) Driver for compressor: 150g

Figure 4. Mobile system for the muscle suit.

B. System configuration

In order to examine the muscle suit's capabilities, we first apply open loop control; i.e., inject compressed air to actuators. The system requires a compressor, a PC, and an electropneumatic regulator. The electropneumatic regulator controls the output of compressed air according to an analogue signal from the PC. Thus, the control system is simple, and we realize a mobile, compact system (4.6 kg in total) as shown in Fig.4.

C. Muscle suit prototype

We use a doll (for bandage exercise made by Kyoto Science Co., Ltd., 40 cm width, 25 cm depth, 150 cm height, and about 15 kg weight) in order to examine whether we could move a person wearing the muscle suit. We check arms for their motion, and in the future we plan to implement the motion of the entire body and walking.

Abduction Bending an elbow

Figure 5. Motion examples by using a life-size doll.

Fig.5 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.5, the muscle suit can lift up the arm (abduction) up to about 40 degrees, and this seems to be the limit. Abduction motion is the most difficult to implement, because of the weight of the arm. Therefore, if we can implement abduction motion by the muscle suit, we can also realize the other motions of the upper limb, we have to think about the structure of the muscle suit though.

IV. Armor-type Muscle Suit

A. Issues of muscle suit

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, we must say that realizing the full range of motion of a human by a muscle suit is very difficult.

Also, because of slippage and slack of wear as illustrated in Fig6, displacement of the muscle suit involves loss; i.e., the full stroke of actuator contraction is not directly conveyed to the muscle suit. This is also the reason why the muscle suit imposes a limitation on range of motion. In addition, reducing slippage and/or slack of wear requires tight fit to the body, making the wearer uncomfortable and being difficult to undress wear.

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 muscles.

As we mentioned above, the issues involved in the muscle suit are summarized as follows;

1. Limitation on range of motion
2. Slippage and slack of wear
3. Tight fit
4. Difficulty in undressing wear
5. Heavy load to bones and joints.

Figure 6. Examples of slippage and slack.

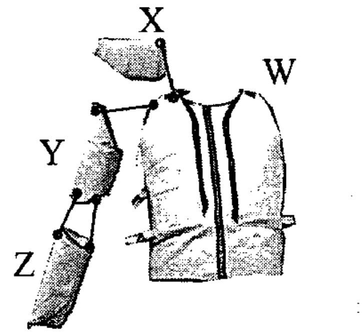


Figure 7. Armor-type muscle suit

B. Concept of armor-type muscle suit by soft frame

To overcome these issues, we have proposed application of the armor structure. That is to say, we prepared a cylindrical garment having some degree of stiffness (called a soft frame) for each part of body without metal, assembled elements for constructing the armor (armor-type muscle suit) as shown in Fig.7, and mounted actuators on it. Dots connected by bold lines describe the connecting point for each part. Because the soft frame consists of urethane board (5mm thickness) and fabric, the armor-type muscle suit is light, and has stiffness for retaining its shape when the wearer moves.

By using a soft frame, which has some degree of stiffness, we can avoid slippage and slack of wear (issue 2), and displacement of the actuator is conveyed directly to the armor-type muscle suit. If then we can control the motion of armor to realize the same range of motion of a human, the wearer might be able to control his movement to achieve the full range of motion (issue 1). Since the wearer is allowed to move inside of the armor-type muscle suit and the soft frame has some degree of stiffness, tight fit is not required (issue 3) and easy to undress wear (issue 4). Moreover, since the wearer is moved by contacting the surface (not point contact) of the soft-frame and he/she does not have to use his/her bones and joints as a brace, stress and/or heavy load are not imposed on bones and joints (issue 5).

C. Development of armor-type muscle suit

Let us show you how the armor-type muscle suit works. We first try to realize abduction motion, which, as we mentioned above, we think is the most difficult upper body motion. Actually, in case of human, it is required more than 10 muscles with complex combination for abduction as well as spherical joint. We then can say that if we accomplish abduction motion, we also complete other motions for upper body by the same manner. Although realizing the full range of human motion might be difficult, it is essential for the muscle suit to attain human motion needed for daily life. From this point of view, we think that it is probably enough to touch the head by a finger and therefore we decided to realize abduction of 90 degrees so that by crooking an elbow, a wearer can touch the head.

First we analyze the simple statics of abduction based on the concept of the muscle suit. As shown in Fig.8, we assign $F[N]$ as the pulling power of the actuator and then the moment $T[Nm]$ for the arm is shown as

$$T = F\sin\alpha \cdot d + F\cos\alpha \cdot a, \tag{1}$$

where

$$\sin\alpha = \frac{ar^2 \pm dr\sqrt{a^2+d^2-r^2} - a^3 - ad^2}{\left(a^2+d^2\right)\sqrt{a^2+d^2-r^2}}.$$

$$\cos\alpha = \frac{ar \pm d\sqrt{a^2+d^2-r^2}}{a^2+d^2}$$

We then obtain

$$T = F\sin\alpha \cdot d + F\cos\alpha \cdot a = F \cdot r. \tag{2}$$

From (2), geometry looks complicated though, we conclude that T depends on just both F and r.

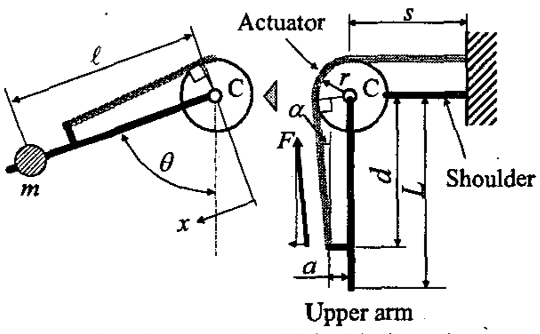


Figure 8. Geometric model for abduction motion

Let us here check the armor structure proposed in Fig.7. Part X looks somehow strange though, it is great asset in terms of getting large T value since we can expect large r value compare to the case which we use only part Y and W. The size of part X is decided from esthetic point of view.

Fig.9 depicts the arrangement of actuators, which we determined by trial and error in order to realize abduction motion. For abduction motion, we use A (1 actuator), B (2 actuators) and C (2 actuators), and for elbow flexion, we use D (2 actuators) and E (2 actuators). Note that in theory, use of actuator A is enough for abduction motion as shown in (2). However, the actuator has constraints with respect to power and contraction rate. In addition, there is limited place to mount the actuator, that is to say, since there are right and left arms, and actuators have to be mounted to each side corresponding to each arm, the length of actuator A must be restricted, i.e., as shown in Fig.9, both ends of actuator are fixed and the maximum length comes to be 450mm. Moreover we can easily imagine the loss of the mechanical structure for abduction motion. For example, the hinge mechanism between part Y and part W does not work well because it is constructed by the soft material. In this sense, to apply part X is again important since we can change r value by controlling the rotation of part X.

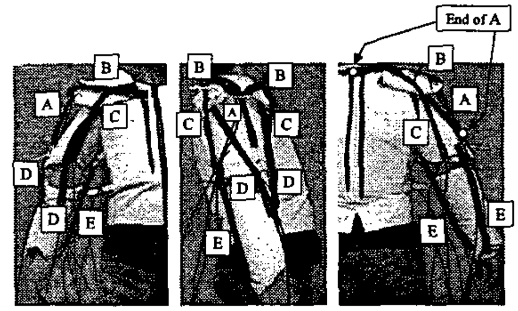


Figure 9. Arrangement of actuators

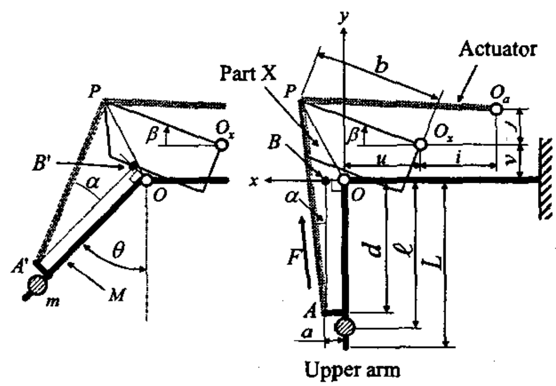


Figure 10. Geometric model of the armor-type muscle suit

D. Analysis of armor-type muscle suit

Fig.10 illustrates the geometric model of the armor-type muscle suit. O, O_x, and O_a depict the center of the arm rotation, one of part X, and one end of mounting point for actuator A respectively. M and m show the weight for the arm and an additional load. M is assumed evenly distributed. In order to estimate the effect of part X at Fig.7, part X is illustrated in Fig.10. Thus Fig.10 describes the geometric model of the right-side armor-type muscle suit without clear shape of part W, Y, and Z at Fig.7. X-Y coordinates for each point are described as

$$\left.\begin{aligned}
&P(x_P, y_P) = (b\cos\beta - u, b\sin\beta + v)\\
&A(x_A, y_A) = (a, \ -d)\\
&A'(x'_A, y'_A) = (x_A\cos\theta - y_A\sin\theta, x_A\sin\theta + y_A\cos\theta)\\
&B(x_B, y_B) = (a, \ 0)\\
&B'(x'_B, y'_B) = (x_B\cos\theta - y_B\sin\theta, x_B\sin\theta + y_B\cos\theta)\\
&\overrightarrow{A'P} = (x_{A'P}, y_{A'P}) = (x'_A - x_P, y'_A - y_P)\\
&\overrightarrow{A'B'} = (x_{A'B'}, y_{A'B'}) = (x'_A - x'_B, y'_A - y'_B)\\
&\cos\alpha = \frac{\overrightarrow{A'P}\cdot\overrightarrow{A'B'}}{\left|\overrightarrow{A'P}\right|\cdot\left|\overrightarrow{A'B'}\right|}
\end{aligned}\right\} \tag{3}$$

Table 1 Values for each parameter of the muscle suit

Upper arm		Others	
a	0.07m	b	0.17m
d	0.15m	u	0.075m
ℓ	0.25m	v	0.075m
L	0.62m	i	0.095m
M	1.3Kg	j	0.025m

Values for each parameter are shown in Table 1. For analysis explained below, we use the life-sized doll again and therefore M value in Table 1 is for the doll. And we apply 0.4MPa to the actuator which is guaranteed for the use of the actuator.

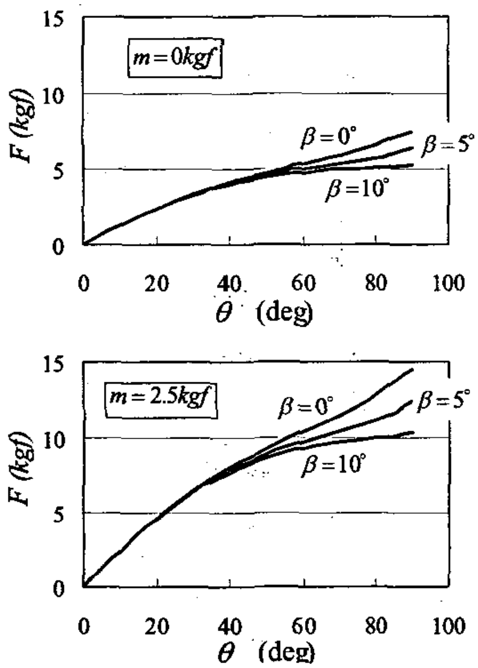


Figure 11. Effect of β in terms of θ and F

Let's first discuss the effect of β which indicates the rotation angle of part X. Note that we decide the size of b for part X as 0.17m from esthetic point of view. The moment $T_A[Nm]$ for the arm rotation is calculated as follows.

$$T_A = \int_0^L \frac{Mg\sin\theta}{L}dx \cdot x + \ell \cdot mg\sin\theta \tag{4}$$

If we apply values of Table 1, we obtain

$$T_A = (3.95 + \ell \cdot mg)\sin\theta . \tag{5}$$

Equation (1) and (4) and/or (5) should be equal and by using these equations, we obtain F corresponding to angle θ and β. Figure 11 exhibits the calculation result. Because of limited space for mounting and contraction rate of actuator B, it is known that 10° is maximum value for β. Note that the average weight of the human arm for 60kg weight male is 3kg. In this case, equation (4) and/or (5) comes to $T_A = 9.1 \cdot \sin\theta$. In order to confirm whether the armor-type muscle suit has capability to lift up human arm, we then apply 2.5 kg as m so that equation (4) and/or (5) becomes $T_A = 9.2 \cdot \sin\theta$.

From Fig.11, we find that, if β has large value, less power is required for uplifting the arm. We can say that part X is effective for realizing abduction motion.

We assign ε_r for the contraction rate required to realize θ geometrically and ε_e for the one obtained from F by using Fig.3 for implementing θ as shown in Fig.11. Fig.12 displays the relation between ε_r and ε_e, when $\beta = 10^\circ$. If ε_r is smaller than ε_e, the arm is uplifted because of large power of F. In the opposite case, since F does not have enough power, the arm does not realize θ expected. As the result, the arm goes up to the crossing point of ε_r and ε_e, i.e., 79° for $m = 0kg$ and 73° for $m = 2.5kg$. We find that abduction of 90° does not realized. We then propose to use actuator C so that part Y gets close to part X and then we achieve uplift of more than 90 degrees.

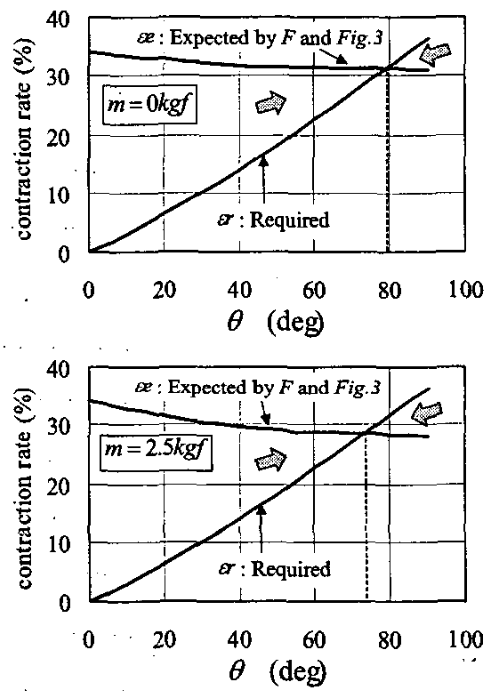
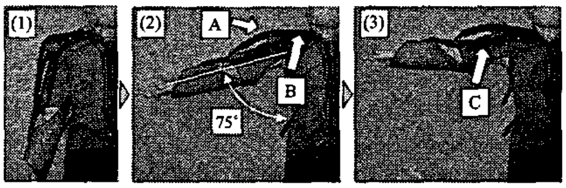


Figure 12. Relation between ε_r and ε_e ($\beta = 10^\circ$)

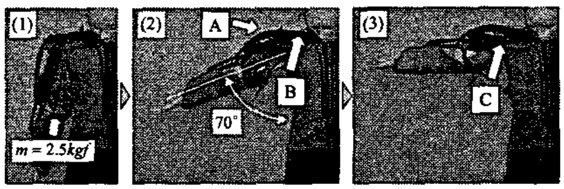
E. *Abduction motion by armor-type muscle suit*

To investigate this analysis, we undertake the experiment by using the life-size doll shown in Fig.13 when we apply 0.4MPa. By using actuator A and B (Fig.13 (2)), the arm is lifted up to about 75° ($m = 0kg$) and 70° ($m = 2.5kg$). We find that θ we have expected is almost realized. Successively, by use of actuator C, part Y is pulled up further, and in total we achieve uplift of about 90 degrees (Fig.13 (3)).

As shown in Fig.14, we had several people wear a prototype of the developed armor-type muscle suit. Values after a subject number express height, bust, and circumference of the upper arm. Although subject V has a problem, possibly because of an oversized circumference of the upper arm, we find that the armor-type muscle suit has some flexibility in size adaptation. Therefore, we expect that we will have to prepare only S, M, and L size armor-type muscle suits such as a normal wear and do not have to worry much about size adjustment and/or fitting. In addition, by wearing underwear, the subject can maintain personal hygiene and adjust the fit.



(a) m = 0kgf

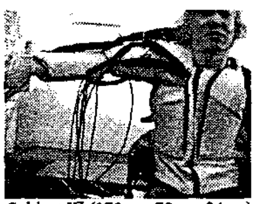


(b) m = 2.5kgf

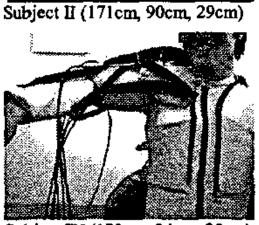
Figure 13. Estimation of abduction by using a life-size doll

Subject I (162cm, 87cm, 27cm)

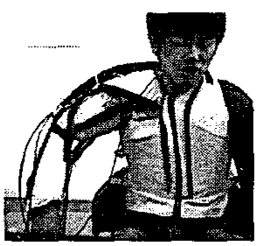
Subject II (171cm, 90cm, 29cm)



Subject III (170cm, 79cm, 24cm)



Subject IV (172cm, 94cm, 29cm)



Subject V (170cm, 95cm, 34cm)

Figure 14. Application to several subjects: values in parentheses are "height", "bust" and "circumference of the upper arm" respectively

V. Concluding Remarks

We proposed a muscle suit as new robot technology and confirmed its feasibility for supporting human movement physically and directly. The muscle suit uses a McKibben artificial muscle driven by air pressure, which is flexibly deformable. It is sewn in a suit that uses human bone as a supporting pole to pull it by contraction, producing motion. We found that the muscle suit is feasible, by manufacturing a muscle suit prototype of the right arm and using a life-sized doll to check motion.

However, our experiments show that the prototype system involves several issues; i.e., limitation of range of motion, slippage and slack of wear, tight fit, difficulty in undressing wear, and application of a large load to bones. To overcome these issues, we propose the armor-type muscle suit and investigate its feasibility. Since abduction is the most difficult upper limb motion, we aimed to realize it. By geometric analysis and an experiment, we show how to realize abduction motion by using the armor-type muscle suit. The experiment using an armor-type muscle suit also showed that it has flexibility in size adaptation.

Currently we have been investigating how to realize other motions in terms of upper limb and adequate movement for the wearer. Also we have been developing the interface by which a wearer can easily control the motion of the muscle suit. Furthermore we plan to manufacture a test system for a commercial product.

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