Advanced Robotics

ISSN: 0169-1864 (Print) 1568-5535 (Online) Journal homepage: https://www.tandfonline.com/loi/tadr20

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To cite this article: Hiroshi Kobayashi, Akitaka Uchimura, Yujiro Isihida, Taichi Shiiba, Kazuaki Hiramatsu, Makoto Konami, Taisuke Matsushita & Yutaka Sato (2004) Development of a muscle suit for the upper body—realization of abduction motion , Advanced Robotics, 18:5, 497-513, DOI: 10.1163/156855304774195046

To link to this article: https://doi.org/10.1163/156855304774195046

Published online: 02 Apr 2012.

Advanced Robotics, Vol. 18, No. 5, pp. 497–513 (2004)

Also available online - www.vsppub.com

Full paper

Development of a muscle suit for the upper body — realization of abduction motion

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Received 15 July 2003; revised 24 December 2003; accepted 25 January 2004

Abstract—A ‘muscle suit’ that will provide muscular support for the paralyzed or those otherwise unable to move unaided is being developed. The muscle suit is a garment without a metal frame that uses McKibben actuators driven by compressed air to produce motion. Because the actuators are sewn into the garment, no metal frame is needed, making the muscle suit very light and cheap. These features are completely different from conventional methods for supporting humans. In this paper, the basic concept and advantages of the muscle suit are first described. In order to verify the feasibility of the basic concept, a prototype system is mounted on a life-size doll. This allows for the limitations of the original design to be identified. Next, an armor-type muscle suit is proposed in order to overcome some of the prototype’s limitations. A full-range abduction motion, which is determined to be the most difficult upper body motion, is realized through geometric analysis and experimentation. In the future, the remaining arm motions will be investigated and implemented.

Keywords: Muscle suit; wearable robot; muscular support apparatus; McKibben artificial muscle; abduction motion.

1. INTRODUCTION

Industrial robots have been the driving force of the technological establishment of Japan, which has produced a wide variety of low-cost, high-quality products. Japan is home to 60% of the world’s industrial robots, which do not interact with personnel, although more than 90% are made in Japan. Robots used in building or construction are classified as industrial robots, because they do not interact

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directly with humans, who must take safety precautions such as wearing helmets. Amusement and entertainment robots are classified as robots for business use.

Meanwhile, Honda ASIMO and Sony AIBO have been marketed for an aging society where the number of children is declining. For this reason, robot technology that supports daily life in a human environment has become increasing popular, including special environments in the field of medicine. According to their specific applications, these robots are classified as medical, nursing care, personal, humanoid or coexistence robots.

One of the current trends in robot evolution is the development of robots that support human daily life. Few of these robot technologies, though, provide physical support or direct human assistance. This paper introduces a muscle suit [1, 2], a wearable robot that directly and physically supports human movement. Kazerooni is developing a robot called the Extender [3] that extends and/or augments human power. This huge robot arm device attaches to a human arm. Although the Extender is a wearable robot, it is not intended for supporting human daily life. Another power-assist suit [4] and a power-assist apparatus called HALL [5] 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. The purpose of the muscle suit is to help a patient who normally needs assistance, move unaided. It could also prove useful to a manual worker. The patient can willfully control his movement with the muscle suit, which provides both muscular and emotional support. In addition, the lack of a metal frame allows the muscle suit to be lightweight, making it realistic to use in daily life.

This paper describes the muscle suit concept and verifies its feasibility by testing a prototype system. Although the muscle suit works to some degree, the garment severely restricts the range of motion. To overcome this limitation, an armor structure using a soft frame is proposed. Among the movements of the upper body, abduction is the most difficult to augment, because of the weight requirements and range of motion. The development of the armor-type muscle suit places special emphasis on the abduction motion.

Section 2 describes the overall muscle suit concept and Section 3 tests the prototype system, with emphasis on physical support and availability. During this testing process, several issues emerge. Section 4 attempts to overcome these obstacles by describing a more appropriate armor-type muscle suit. Geometric analysis and experimentation are then used to test the proposed system's capability.

2. MUSCLE SUIT CONCEPT

This section introduces a wearable muscular support apparatus (muscle suit) 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 Fig. 1, both ends of an actuator are sewn into a garment. Upon

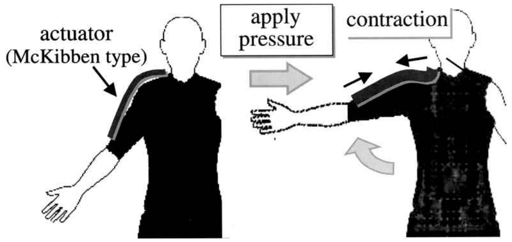


Figure 1. Principle of operation of a muscle suit.

receipt of pressurized air, the actuator contracts and the garment pulls, lifting the wearer's arm.

This new muscle suit robot technology, which will be incorporated in a new entertainment robot, is designed to directly support a variety of people. The muscle suit boasts the following features:

- Enables the person wearing the suit to produce all types of motion.
- Uses a pneumatic actuator (see Section 3) called the McKibben artificial muscle, which is lightweight, flexible and generates a large output.
- Provides lightweight physical support sufficient for augmenting muscular strength without the use of a metal frame. Instead the actuator itself is sewn into the suit.
- Enables independent movement by the wearer, thereby enhancing independence and providing encouragement.
- Can be applied to lightweight or large humanoid and entertainment robots. If only an inner skeleton is employed, the muscle suit is simply worn by the inner skeleton.

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, the robot's actuators resemble muscles, which simulate the smooth and flexible characteristics of human movement. Since the muscle suit is directly attached to a human, it is based on a different concept than conventional robot technology.

3. PROTOTYPE OF THE MUSCLE SUIT

3.1. 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 [6]. It is small lightweight, simple, soft, flexible and has no stiction [4].

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 both

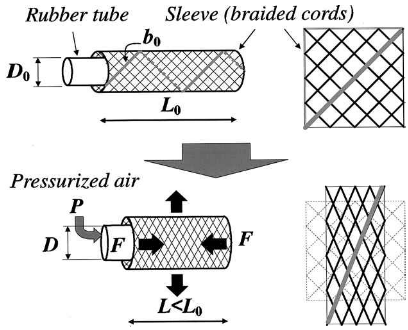


Figure 2. Structure of a McKibben artificial muscle.

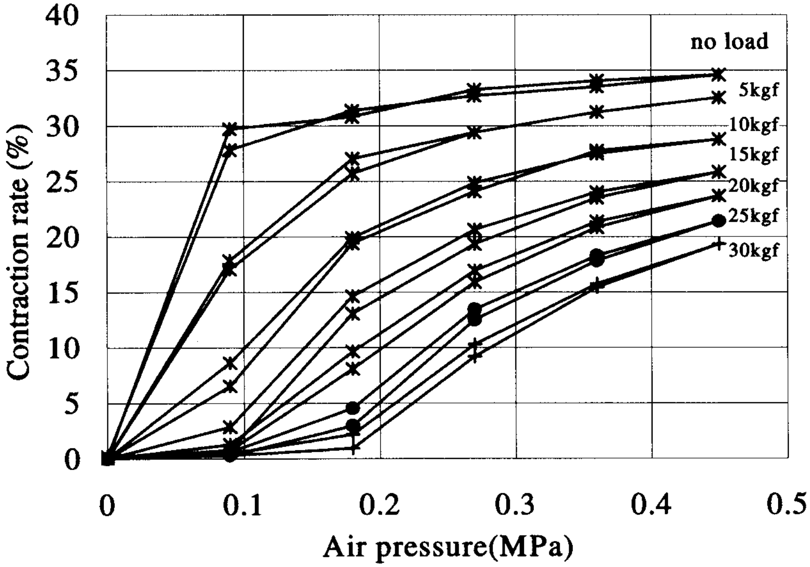


Figure 3. Relationship between relative air pressure, contraction rate and load.

ends to fittings. As shown in Fig. 2, when the internal bladder is pressurized, the highly pressurized air pushes against the inner surface and against the external shell, increasing 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.

Figure 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 kg.

As previously mentioned, the McKibben-type actuator is very soft and flexible. The muscle suit takes advantage of these features. The actuators are arranged so that they conform to the curved surfaces of the wearer’s body.

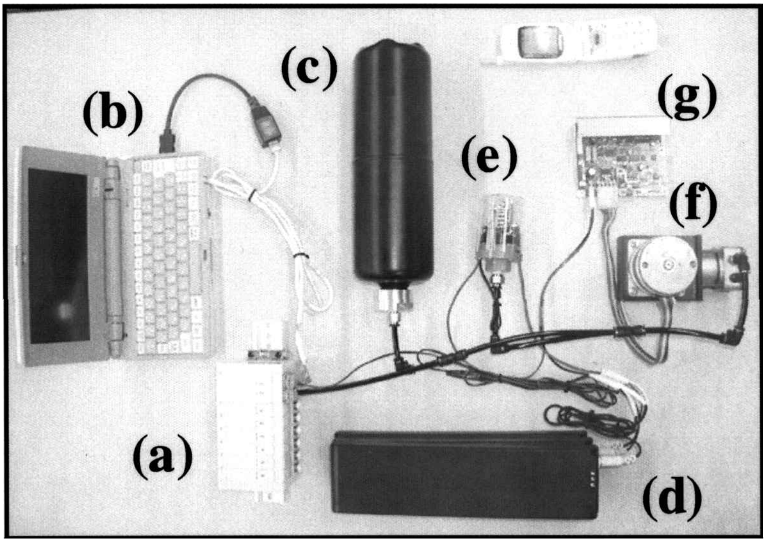


Figure 4. Mobile system for the muscle suit. (a) Electropneumatic regulator: 770 g. (b) PC: 750 g. (c) Tank: 880 g. (d) Battery: 660 g. (e) Pressure switch: 280 g. (f) Compressor: 1200 g. (g) Driver for compressor: 150 g.

3.2. System configuration

Open loop control is used to examine the capability of the muscle suit. More specifically, compressed air is injected into the actuators. This system requires a compressor, a PC and an electropneumatic regulator. The electropneumatic regulator controls the compressed air output according to an analog signal from the PC. Thus, the control system is simple, and the mobile, compact and lightweight (4.6 kg in total) system displayed in Fig. 4 proves viable.

3.3. Muscle suit prototype

A doll is used (for bandage exercises, made by Kyoto Science, 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 arms was checked. The motion of the entire body, including walking, will be examined in the future.

Figure 5 shows the doll's arm. The doll has 6 d.o.f.: three translational d.o.f. (forward and backward, left and right and vertical for the shoulder), one at the upper arm for torsion, one at the elbow for bending, and one at the wrist for moving the palm left and right. An additional d.o.f. is added for the human wearer for moving the palm forward and backward, for a total of 7 d.o.f. As shown in Fig. 6, this study implemented 6 d.o.f. for the doll's arm with seven actuators (A–G). The number of actuators is greater than the d.o.f., because two actuators (D and F) are employed for inward and outward rotation, respectively. These two actuators combine to realize one torsion d.o.f. Two actuators (A and B) are also used to raise the entire arm,

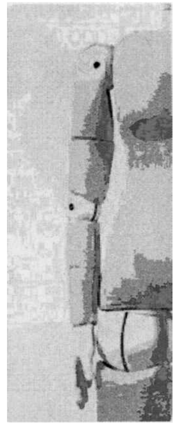


Figure 5. Doll arm for the muscle suits prototype.

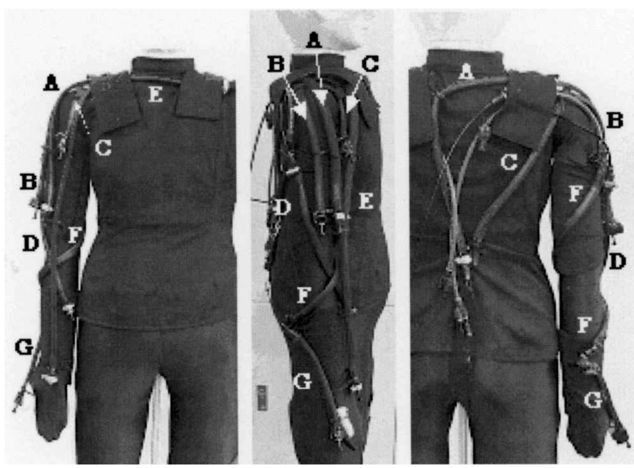
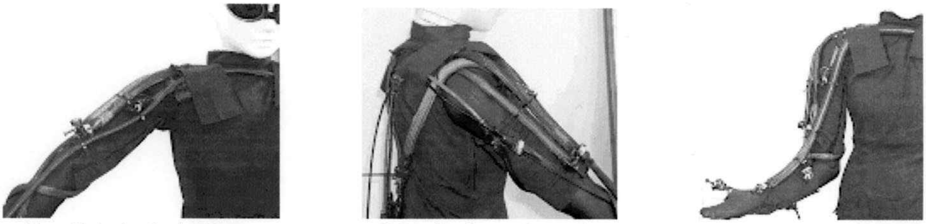


Figure 6. Arrangement of actuators.

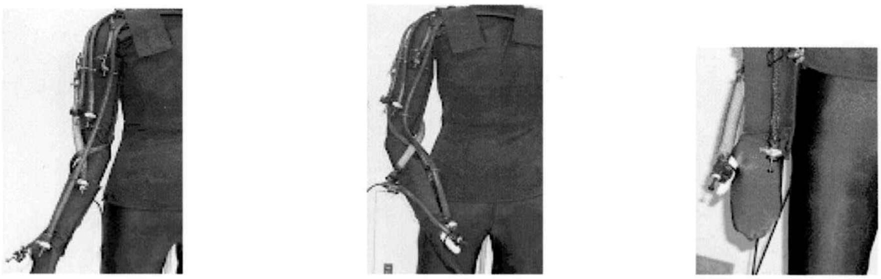
due to its weight. Increasing the number of actuators enhances the muscle suit's power, imparting robustness against failure. Combining this motion with forward and backward motion (via actuator C) enables horizontal motion.

Figure 7a–e shows abduction motion, moving the arm forward, bending the elbow, outward and inward rotation of the arm, and the motion of the wrist. These motions commence when 0.4 MPa is applied to the actuator. The length and mounting position of the actuators and other parameters were determined experimentally. The resulting configuration confirmed that a human could wear the muscle suit and that the skeleton robot in conjunction with human physical support could implement the motions corresponding to the d.o.f. described above.

During this experimentation, however, limitations in the muscle suit's range of motion were detected. For example, Fig. 7a shows that the muscle suit is able to lift an arm (abduction) up to a maximum of about 40°. The abduction motion



(a) Abduction by A & B (b) Moving the arm forward by C (c) Bending an elbow by E



(d) Outer revolution of arm torsion by D (e) Inner revolution of arm torsion by F (f) Wrist motion by G

Figure 7. Motion examples by using a life-size doll.

is the most difficult to implement, because of the arm's weight. Therefore, if the abduction motion can be successfully implemented, the other arm motions should be realizable. The entire muscle suit structure will have to be considered during this implementation process.

4. ARMOR-TYPE MUSCLE SUIT

4.1. Issues of the muscle suit

Muscles of mammals are attached directly to bones, giving them a very wide range of motion, largely because the distance between the joint and the end of the 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 the end of an actuator must be greater than the distance between a joint and an end of a muscle. For this reason, 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. 8. These losses are the primary reason why the muscle suit experiences range-of-motion limitations. Reducing slippage and/or slack of wear requires a tight fit. This makes dressing difficult and reduces comfort.

Moreover, because the muscle suit mounts on the human skeleton, bones and joints are forced to withstand the load produced by the actuators. Thus, the muscle suit may apply a large load to the wearer's joints and muscles.

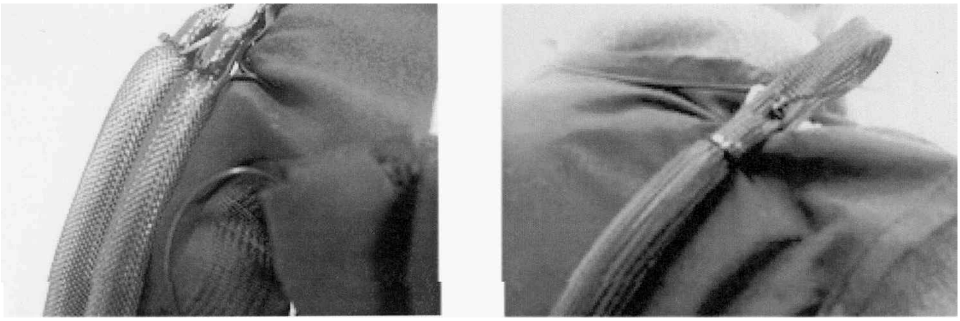


Figure 8. Examples of slippage and slack.

The current issues concerning the muscle suit are summarized below:

(i) Range of motion limitations.
(ii) Slippage and slack of wear.
(iii) Tight fit.
(iv) Difficulty in dressing and undressing.
(v) Heavy load on bones and joints.

4.2. Concept of an armor-type muscle suit using a soft frame

To overcome these issues, an armor structure has been proposed. More specifically, a cylindrical garment exhibiting a degree of stiffness (called a soft frame) was developed for each body part. The armor-type suit is displayed in Fig. 9. This frame was fabricated without metal and the actuators are mounted directly on it. In Fig 9, the dots connected by bold lines denote the connecting points for each part. Because the soft frame is comprised of a 5-mm thick urethane board and fabric, the armor-type muscle suit is light and able to retain its shape when the wearer moves.

By using a soft frame with a degree of stiffness, slippage and slack of wear can be reduced because the actuator's displacement is conveyed directly to the armor-type muscle suit. Then, if the armor's motion were able to match human movement, the wearer might be able to achieve a full range of motion. Because the wearer is allowed to move inside the armor-type muscle suit and the soft frame has some degree of stiffness, a tight fit is not required. This makes it easy for the wearer to dress and undress. Moreover, since the wearer is moved by contacting the surface (not point contact) of the soft-frame and the wearer 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.

4.3. Development of an armor-type muscle suit

This section describes the development of the armor-type muscle suit. The first challenge was to achieve full abduction motion, which, as mentioned above, is the most difficult upper body motion. This motion in humans is requires a complex

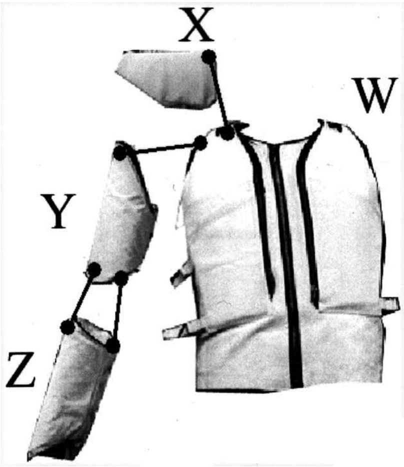


Figure 9. Armor-type muscle suit.

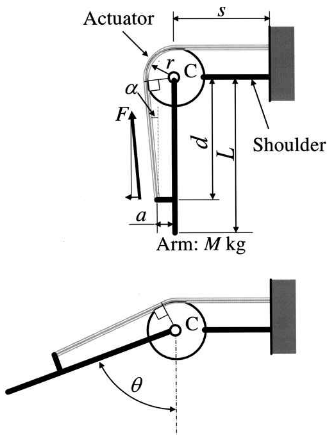


Figure 10. Geometric model for abduction motion.

combination of more than 10 muscles, in addition to a spherical joint. It is assumed that if the abduction motion can be successfully achieved, the other upper body motions can also be simulated as well. Although realizing the full range of human motion is difficult, it is essential for daily life tasks. It is assumed that if the wearer is able to touch his head with a finger, most daily tasks can be performed. Therefore, a total abduction of 90° is the objective for this motion.

First, the simple statics for abduction is analyzed, based on the muscle suit concept. As shown in Fig. 10, F (N) represents the actuator's pulling power and T (Nm) denotes the arm's moment, which can be calculated by

$$T = F \sin\alpha \cdot d + F \cos\alpha \cdot a = F \cdot r. \quad (1)$$

Equation (1) indicates that T depends solely on F and r.

The mechanism of human abduction, shown in Fig. 11, is now discussed. The shoulder blade rotates during the arm motion. This indicates that the armor-type muscle suit should also contain a similar mechanism because it is worn by a human being. Otherwise the shoulder blade will interfere with the armor and disturb its motion. Part X in Fig. 9 performs this task. Additionally, from a geometric point of view, part X aids in producing large T values since it creates a larger r value, when compared to using only parts Y and W. The size of part X was determined from an aesthetic point of view.

Figure 12 depicts the arrangement of actuators, which were positioned using trial and error, for abduction motion. In Fig. 12, A (one actuator), B (two actuators) and

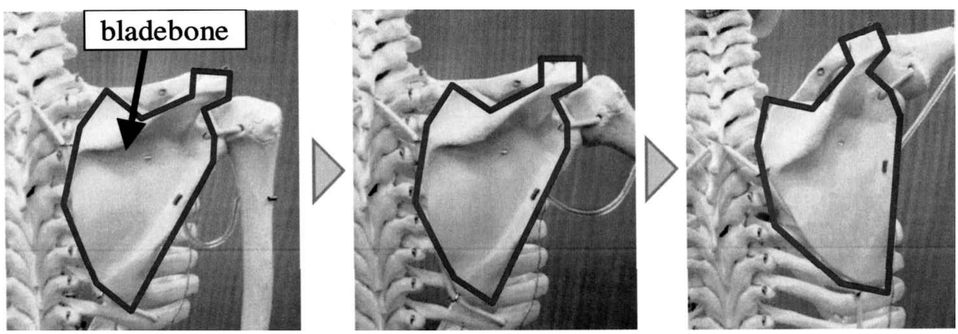


Figure 11. Mechanism for abduction motion.

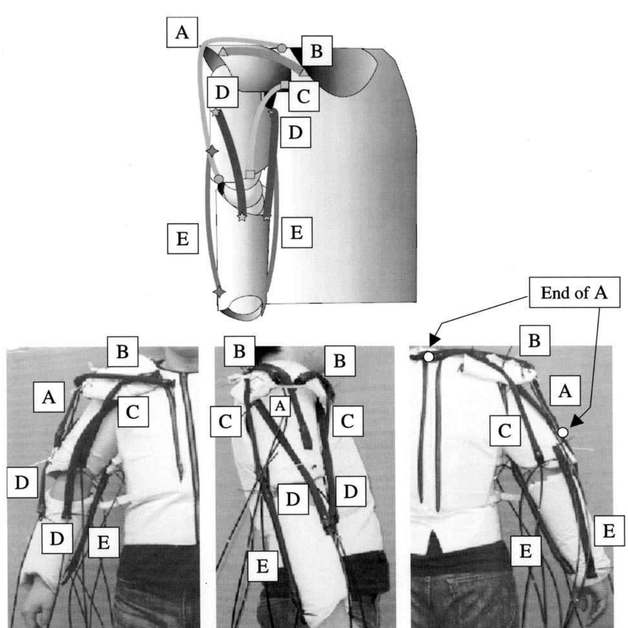


Figure 12. Arrangement of actuators.

C (two actuators) were used to produce the abduction motion, and D (two actuators) and E (two actuators) were used to produce elbow flexion. In theory, actuator A should be enough for achieving the abduction motion. The power and contraction rate constraints on the actuator, however, limit its effectiveness. In addition, the mounting locations for the actuator are also limited. The actuators need to be mounted on each side of each arm, so the length of actuator A must be restricted. As shown in Fig. 12, both ends of the actuator are fixed and the maximum length is determined to be 450 mm. Moreover, the mechanical structure needed for the abduction motion is easily lost. For example, the hinge mechanism between parts Y and W does not work well because it is constructed of the soft material. Therefore, part X is important since the r value can be adjusted by controlling the rotation angle of part X.

4.4. Analysis of an armor-type muscle suit

Figure 13 illustrates the geometric model of the armor-type muscle suit. O, O_x and O_a denote the center of the arm rotation, the center of part X and the mounting point for actuator A, respectively. M and m represent the weight of the arm and the additional loadas shown in Fig. 13. M is assumed evenly distributed. In order to estimate the effect of part X in Fig. 9, a more detailed depiction of part X is provided in Fig. 13, which displays the geometric model of the right side of the armor-type muscle suit without interference from parts W, Y and Z.

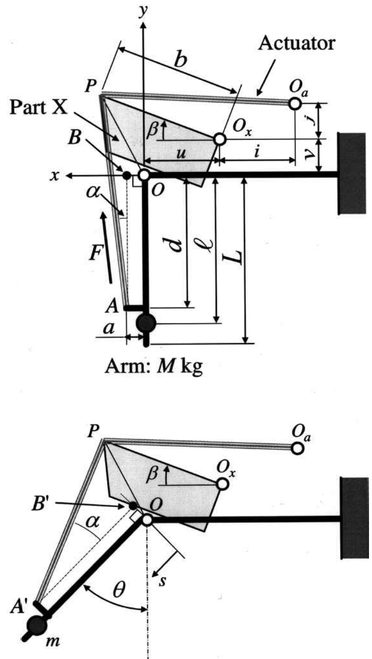


Figure 13. Geometric model of the armor-type muscle suit.

Table 1.
Values for each parameter of the muscle suit

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

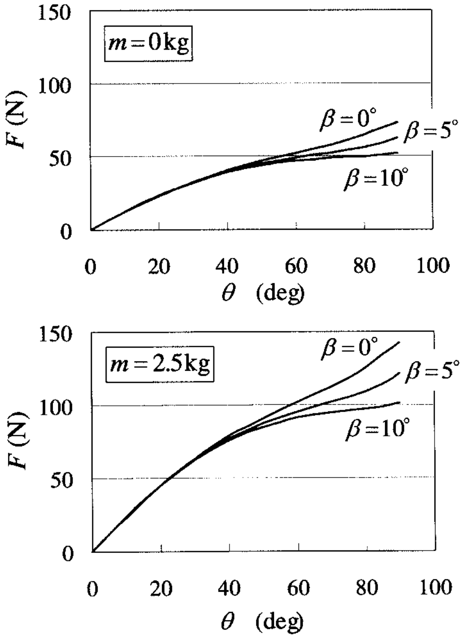


Figure 14. Effect of β in terms of θ and F.

Values for each parameter are shown in Table 1. The analysis explained below was generated using the doll displayed in Fig. 5 and, therefore, the M value in Table 1 is for the doll; 0.4 MPa is applied to the actuator. This load lies within the actuator's guaranteed operational range.

The effect of β, which represents the rotation angle of part X, is now discussed. The size of b in part X was chosen to be 0.17 m, based upon aesthetics. The moment T_{A} (Nm) for the arm rotation can be calculated from:

$$T_{\mathrm{A}} = \int_0^L \frac{Mg\sin\theta}{L}\,\mathrm{d}s \cdot s + \ell \cdot mg\sin\theta. \tag{2}$$

Substituting the Table 1 values into (2), we obtain:

$$T_{\mathrm{A}} = (3.95 + \ell \cdot mg)\sin\theta. \tag{3}$$

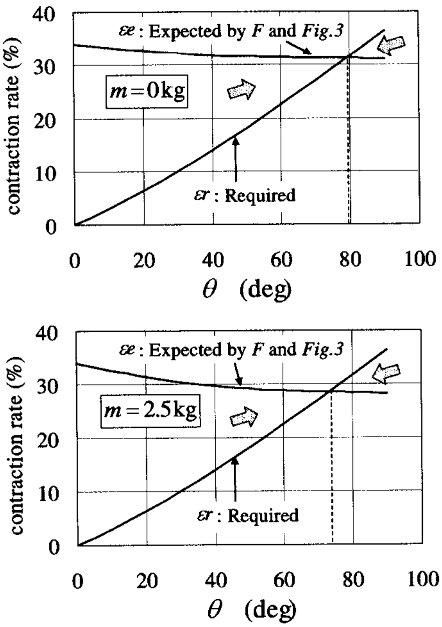


Figure 15. Relation between εr and εe ($\beta = 10°$).

Equations (1), (2) and (3) are equivalent. The F value corresponding to angles θ and β can now be obtained. Figure 14 displays the result. Due to actuator B's limited mounting space and contraction rate, it is known that 10° is the maximum value for β. The average weight of a 60 kg human's arm is 3 kg. For this case, (2) and (3) simplify to $T_{\mathrm{A}} = 9.1 \cdot \sin\theta$. $m = 2.5$ kg weight is applied to the system to verify whether the armor-type muscle suit is capable of lifting up a human arm, since in this case (2) and (3) become $T_{\mathrm{A}} = 9.2 \cdot \sin\theta$, which is bigger than $T_{\mathrm{A}} = 9.1 \cdot \sin\theta$.

Figure 14 suggests that the larger the value of β, the less power is required for lifting the arm. Thus, part X is vital for realizing abduction motion.

εr represents the contraction rate required to geometrically produce θ and εe is the value obtained from F in Fig. 3 for implementing θ, as shown in Fig. 14. Figure 15 displays the relationship between εr and εe when $\beta = 10°$. If εr is smaller than εe, the large power of F is able to lift the arm. On the other hand, F does not have enough power, the arm is not able to generate the expected θ. As the result, the maximum rotation for the arm is the intersection of εr and εe, which is 79° when $m = 0$ kg and 73° when $m = 2.5$ kg. In both cases, an abduction of 90° is not achieved. In an attempt to solve this problem, the addition of actuator C is proposed so that part Y can move closer to part X.

4.5. Abduction motion by an armor-type muscle suit

To investigate this proposal, an experiment using the doll and an additional 0.4 MPa applied load is conducted, as shown in Fig. 16. Using only actuators A and B, the

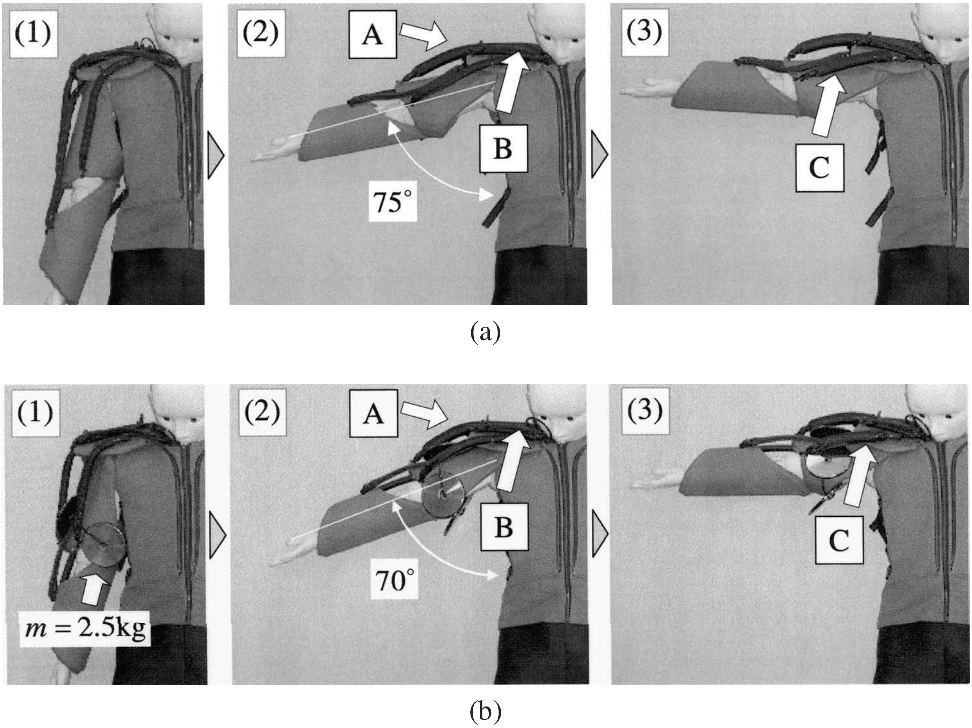


Figure 16. Estimation of abduction by using a life-size doll. (a) $m = 0$ kg; (b) $m = 2.5$ kg.

arm is lifted up to about 75° when $m = 0$ kg and 70° when $m = 2.5$ kg. These values are close to the target values. When actuator C is added to the system to pull up part Y further, the full 90° lift is successfully achieved.

Several people tried on the armor-type muscle suit prototype, as shown in Fig. 17. These subjects had different height, bust and upper arm circumference measurements. Although subject V experienced a problem, possibly due to an oversized upper arm circumference, the armor-type muscle suit has some flexibility in size adaptation. Therefore, it is expected that the final model will be available in only S, M and L sizes. Armor-type muscle suits will be worn off-the-shelf, without the need for size adjustments and/or fittings. In addition, the subject can maintain personal hygiene by wearing underwear.

5. CONCLUDING REMARKS

A muscle suit has been proposed as a new robot technology and its feasibility for directly supporting physical human movement has been confirmed. The suit uses McKibben artificial muscles driven by air pressure, which are flexibly deformable. The actuators are sewn into a suit that uses either a robotic inner frame or human bone for bracing during contractions that produce motion. The right arm prototype

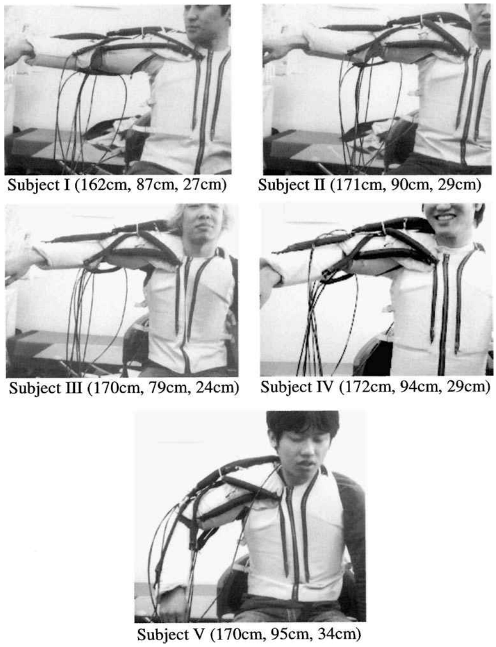


Figure 17. Application to several subjects (values in parentheses are 'height', 'bust' and 'circumference of the upper arm', respectively).

for the muscle suit was manufactured and a life-size doll was used to check its motion.

The initial experiments, however, revealed that the prototype system has several issues, including a limited range of motion, slippage and slack of wear, a tight fit, difficulty in dressing and undressing, and a large load on the human bones. To overcome these issues, an armor-type muscle suit was proposed and its feasibility was investigated. Since abduction is the most difficult arm motion, the design centered on it. Geometric analyses and experiments were performed to verify that the armor-type muscle suit could generate a full-range abduction motion. The experiment also highlighted the suit's size adaptation flexibility.

Thus far, the abduction motion, which no one has succeeded in implementing by just wearing the suit without a metal frame, has been successfully reproduced using the armor-type muscle suit. The next step is to investigate and implement the remaining arm motions. In the future, a test system for a commercial product will be manufactured.

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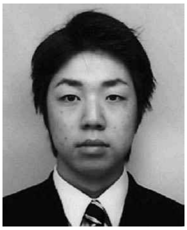

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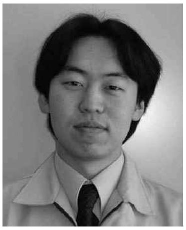

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