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Realization of All Motion for the Upper Limb by a Muscle Suit

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

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 lack of a metal frame and use of McKibben artificial muscle allow the muscle suit to be lightweight, making it realistic to use in daily life. To overcome the basic concept of the muscle suit, the new structure with the mechanical joints and plastic frame is applied. Although Human's range of motion was not fulfilled by the new structure muscle suit, all seven upper limb motions were realized and range of motion might be enough for daily use.

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, though more than 90% are made in Japan. 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 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. An exoskeleton to assist elbow and forearm motion especially for physically weak persons has been also constructed [6] though, it has the same drawback.

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 and rehabilitation. The patient will be able to willfully control his movement with the muscle suit, which provides both muscular and emotional support. In addition, the lack of a main metal frame and use of McKibben artificial muscle allow the muscle suit to be lightweight, making it realistic to use in daily life.

This paper describes the muscle suit concept 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, the mechanical joint with a plastic frame is proposed and all motion for upper limb, i.e. Flexion, Abduction, Inner rotation, Extension, Adduction, Outer rotation, and Flexion of Cubital Joint, is realized after all.

Chapter 2 describes the overall muscle suit concept, and Chapter 3 tests the prototype system, with emphasis on physical support and availability. During this testing process, several issues emerge and then the new muscle suit with the mechanical joint and the plastic frame is proposed to overcome these obstacles in Chapter 4.

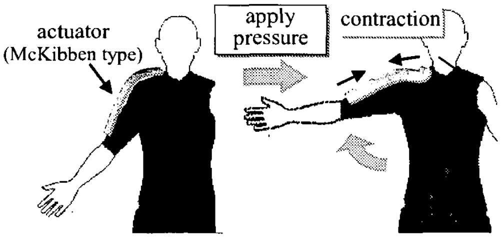

Figure 1: Principle of operation of muscle suit.

2 Concept of Muscle Suit

This chapter 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 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.

This new muscle suit robot technology is designed to

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directly support a variety of people. The muscle suit boasts the following features:

- Enables a person wearing the suit to realize any kind of motion.
- Uses a pneumatic actuator (Chapter 3), 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 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 simulates 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 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 [7]. It is small, lightweight, simple, soft, flexible, and has no stiction [8]. Power-to-weight ratio is vastly outperforming.

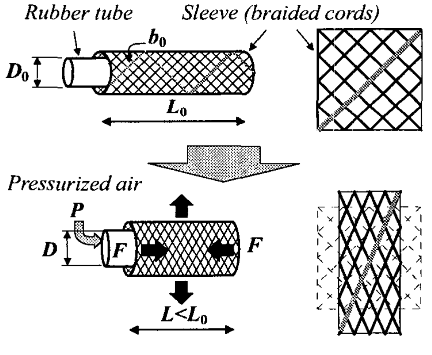


Figure 2: Structure of McKibben artificial muscle

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 kg.

As previously mentioned, 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.

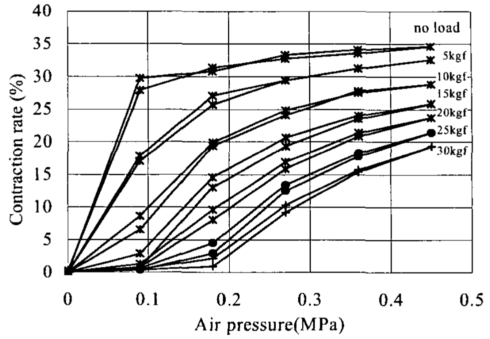
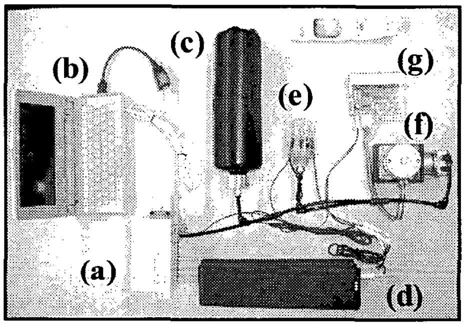


Figure 3: Relationship between relative air pressure, contraction rate, and load



(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.

Abduction Bending an elbow

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

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 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 arms was checked. The motion of the entire body, including walking, will be examined in the future.

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 seems to be the most difficult to implement, because of the weight requirements and range of motion. The muscle suit places special emphasis on it.

4 Development of New Structure Muscle Suit

4.1 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, 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. 6. 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, 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. As we mentioned above, the issues involved in the muscle suit are summarized below;

1. Range on motion limitation
2. Slippage and slack of wear
3. Tight fit
4. Difficulty in dressing and undressing
5. Heavy load on bones and joints.

4.2 Concept of New Structure Muscle Suit

To overcome these issues, the use of the mechanical joint and chloroethene frame connected by mechanical joints have been proposed.

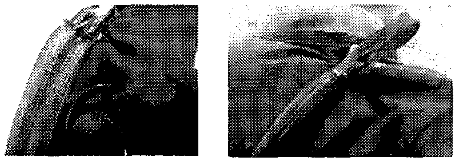


Figure 6: Examples of slippage and slack.

By using a chloroethene 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 muscle suit. If then we can control the motion of the chloroethene frame 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 muscle suit and the chloroethene 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).

4.3 Development of New Structure Muscle Suit

Fig. 7 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. 8 describes the overview of new structure muscle suit. The total weight is 3kg. It is not clear 3kg is heavy or not. The estimation of the weight will investigate in near future though, less than 2kg will be expected if we use FRP instead of chloroethene. Mechanical details are shown in following section.

Since the muscle suit should be easy to dress and undress as a wearable robot, a suit and for the daily use, easy method for dressing and undressing must be proposed.

Fig.9 is our solution. By raising both arms, people can easily dress and undress the muscle suit.

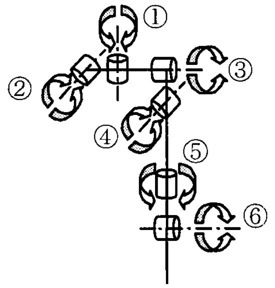


Figure 7: Degree of freedom required for the all upper limb motions.

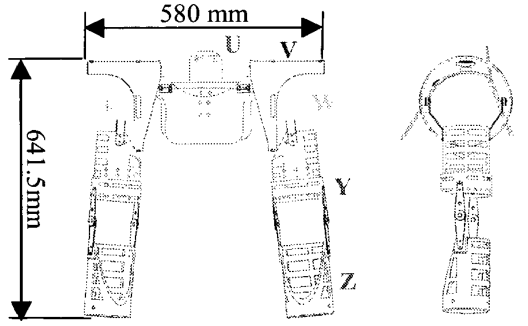


Figure 8: Structure of new muscle suit

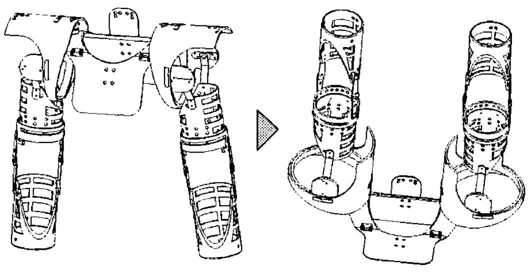


Figure 9: Mechanism for dressing and undressing

4.4 Details of Structure

As shown in Fig.8, new muscle suit consists of 6 types and 12 parts, i.e. U× 1, V × 2, W × 2, X × 2, Y × 2, and Z × 2. Structure and connecting mechanism are explained below in turn.

"U" is constructed by aluminium (3mm thickness) because of easy to produce. It will be changed to FRP soon. As shown in Fig.10, the front panel opens for wearing and protrusion region at back side plays important role for mounting actuators.

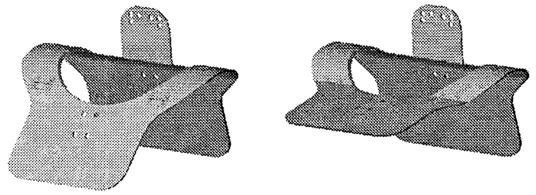


Figure 10: Structure and mechanism of type "U"

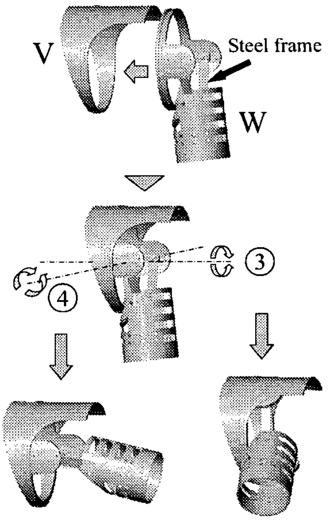


Figure 11: Structure and mechanism of type "V" and "W"

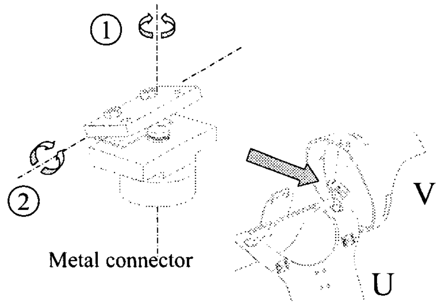


Figure 12: Connecting mechanism for type "U" and "V"

"V" and "W" are basically constructed by chloroethene. Only two thin frames with joints for ④ rotation are made by steel as shown in Fig.11. By making groove on "V" and "W", rotation ③ is realized. In order to connect "U" and "V" and realize ① and ② rotation, metal connecter with 2 DoF described in Fig.12 is used. For elbow bending as shown in Fig.13, i.e. rotation ⑥, two thin frames with joints are again used though, "Z" is basically constructed by chloroethene. For ⑤ rotation, groove is applied.

From mechanical point of view, friction given by groove of chloroethene should be reduced. While the power of actuator is extreme, high speed is not required, and loads for making human wearer move is large, friction is not a serious issue at the moment. We will improve in near future.

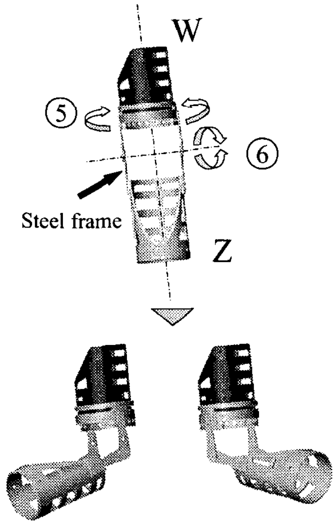


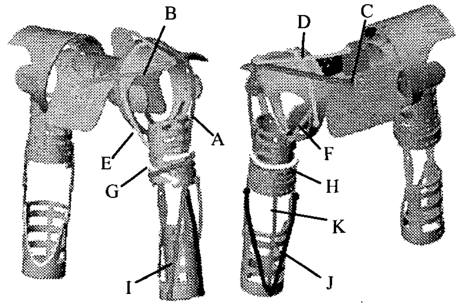
Figure 13: Structure and mechanism of type "W" and "Z"

4.5 Actuator Arrangement

Fig.14 depicts actuator arrangement. 13 actuators are applied for each arm. The arrangement is selected empirically in order to achieve human's range of motion. Table 1 shows combination of actuators required to realize each motion. Because of the limited space, details are not mentioned here. Examples of how to realize motions by combination of actuators are shown in Fig.15.

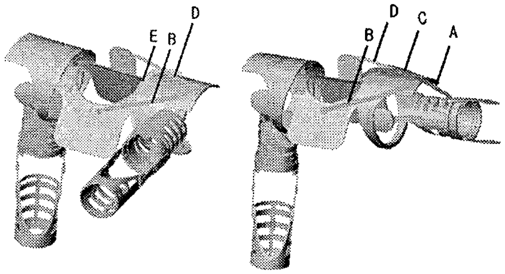
4.6 Realization of the Upper Limb Motion

Fig.16 shows all seven motions realized and Fig.17 displays range of motion achieved by new-structure muscle suit. Except for flexion of cubital joint, range of motion is not satisfied human's one. While touch the mouth from forward and the head from above might be enough for daily life. "Touch the mouth from forward" is realized by combination of shoulder joint flexion, shoulder joint inner rotation, and cubital joint flexion. Also "Touch the head from above" by combination of shoulder joint abduction, shoulder joint outer rotation, and cubital joint flexion. Satisfaction of human's range of motion is our final goal though, new structure muscle suit might be enough for daily use as mentioned above. Moreover it might be possible to realize human's range of motion if the degree of freedom would be restricted.



A: Abducting Brachial Armor
B: Rotating Shoulder Armor 1
C: Rotating Shoulder Armor 2
D: Rotating Shoulder Armor 3
E: Flexing Brachial Armor
F: Extending Brachial Armor
G: Inner Rotating Brachial Armor
H: Outer Rotating Brachial Armor
I: Flexing Anconal Armor 1
J: Flexing Anconal Armor 2

Figure 14: Actuator arrangement



Flexion Abduction

Figure 15: Examples for realizing motion by combination of actuators

Table 1: Combination of actuators for each moition

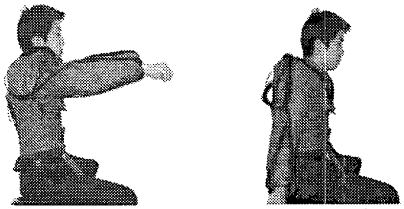
	Motions	Actuators
Shoulder Joint	Flexion	B, D, E
	Extension	C, D, F
	Abduction	A, B, C, D
	Adduction	B, D, E
	Inner rotation	G
	Outer rotation	H
Cubital Joint	Flexion	I, J

5 Concluding Remarks

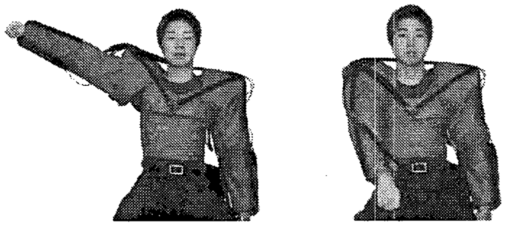
A muscle suit has been proposed as a new robot technology (wearable robot), and its feasibility for directly supporting physical human movement has been confirmed. The suit uses McKibben artificial muscles driven by air pressure, which are flexibly deformable. The actuators are sewn into a suit that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

The 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, a new structure muscle suit with mechanical joints and hard chloroethene frame was applied. Although Human's range of motion was not fulfilled by the new structure muscle suit, all seven upper limb motions were realized and range of motion might be enough for daily use.

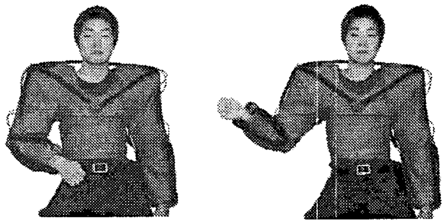
Thus far, all upper limb motion has been successfully reproduced using the new structure muscle suit. There are two goals for the muscle suit, i.e., realization of human's range of motion and control of the muscle suit by the wearer' will. Since first goal was realized to some degree, second goal, i.e. control method, has been currently investigating.



Flexion Extension



Abduction Adduction



Inner rotation Outer rotation

Cubital joint flexion

Figure 16: All seven motions realized

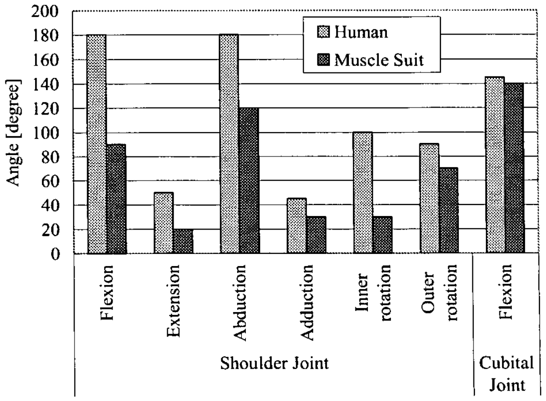


Figure 17: Range of motion realized

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