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Muscle Textile to Implement Soft Suit to Shift Balancing Posture of the Body

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***Abstract*— This study reports on the design and construction of a body support suit based on two novel concepts: muscle textile and shifting the balancing posture of the body. The muscle textile is an active textile composed of soft thin muscles that provides a large supporting force, and is flexible and lightweight. Shifting the balancing posture of the body involves changing its neutral posture while relaxing the muscles, making it easier to perform tasks in uncomfortable positions and simplifying the control system of the support suit. These two ideas are employed herein to design a flexible, light, comfortable, and simple support suit system. We then propose and test a soft suit intended to assist humans in tasks involving unnatural arm positions based on this design. The performed subjective experiments confirmed that the 2 kg soft suit attained a self-weight compensation of up to 120° forward, a reduction of 33% in the integrated electromyogram in the brachialis muscle, and a suppression of 5% of body sway.**

Keywords*— *Physically Assistive Devices, Wearable Robots, Hydraulic/Pneumatic Actuators

I. INTRODUCTION

In recent years, support suits have attracted considerable research interest in terms of assisting people with physical disabilities, reducing labor burden, and other avenues. They have been used in body motion support, agriculture, and construction. Many support suits are designed to support large movements or posture maintenance. Representative exoskeleton suits include the HAL [1] and the Raytheon XOS-2 [2]. The muscle suit [3] was developed to provide lumbar support and help movement through a pneumatic artificial muscle. These support suits can provide a large supporting force because of their hard linkage structure. However, this structure incurs a disadvantage because of its weight. Moving the suits become difficult, and they are uncomfortable for the wearer.

A soft exosuit [5] is a typical endoskeleton suit. An endoskeleton has the advantage of reducing the burden on the wearer's body because of its flexible and light structure. The soft exosuit was developed for support while walking. It operates using wire driving, which makes it lightweight and flexible. However, the supporting force that it provides to the body works along lines, which can sometimes cause a large contact stress. The wired portion can also be uncomfortable to wear.

The soft robot for shoulder support [4] helps movement through a soft textile pneumatic actuator, and is composed of an air tight bladder, an inextensible textile, and flexible plates. Volume increases when air pressure is applied. It then produces force and displacement by expanding. However, it can be an obstacle when users perform certain motions, like twisting the arm.

This study proposes two concepts: muscle textile and shifting the balancing posture of the body. The muscle textile is an active textile composed of soft thin muscles that provides high support, and is flexible and lightweight. The working stress at the point of contact between the human body and the support suit is dispersed because the active textile provides support to the human body on the surface of the body or in wide areas. As a result, the burden on the body reduces, and comfort is improved. The muscle textile flexibility helps the support suit to follow complex motions even in a pressurized state, like twisting the body. Wearing a few layers of suits to implement support for a complex motion in different directions also becomes possible. Such is impossible in conventional support suits because of their bulk and lack of flexibility. Thus, the muscle textile helps realize a layered and expandable support suit. Shifting the balancing posture of the body is a body support method that focuses on changing the neutral point to maintain posture. We define the balancing posture of the body (BPB) as its posture in a relaxed state. For example, the BPB of the arm is usually in a state, where the arm hangs vertically downward. The control for conventional support suits involves actively moving the body. Our method focuses on shifting the BPB. For instance, in artificial pollination, the support suit shifts the BPB of the arm to a raised posture. One advantage of shifting the BPB is the simplification of the control system. In an assistance suit with compliance of the kind we propose, the wearers can adjust their postures using their own force after shifting the BPB to a certain posture. This would apply even to a delicate posture adjustment. These two ideas (i.e., muscle textile and shifting the BPB) help realize a flexible support system that is simple and easy to expand.

We propose and test herein a soft suit designed to assist humans in holding objects in unnatural arm postures, such as

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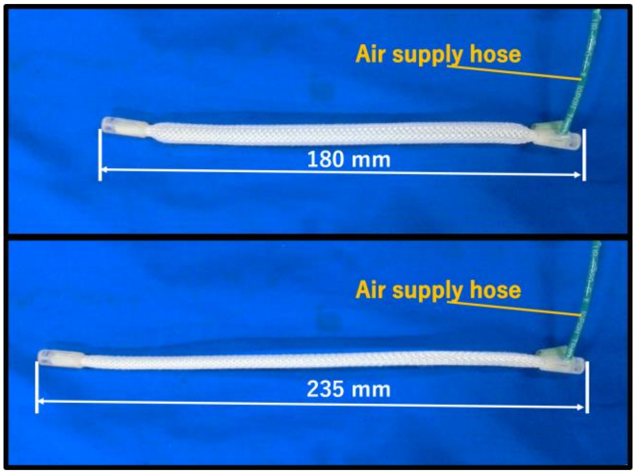

Figure 1. 4 mm soft thin muscle (upper: pressurized state; lower: initial state).

those involved in pollination and construction work, based on the two abovementioned novel technologies. We report on the constituent elements, composition, and evaluation of a prototype suit. Section 2 describes the soft thin muscle constituting the muscle textile and the effect of the overlap of the muscle textiles. Section 3 explains the soft suit design and composition. Section 4 describes the test of our prototype. We conducted an experiment to test the shifting of posture and the effects of reducing the muscle load on the arm and the burden on the entire body.

II. STATICS OF SOFT THIN MUSCLES

A. *Soft Thin Muscles*

The soft thin muscle developed by the authors was a pneumatic-drive artificial muscle with a very small diameter. This muscle was composed of a rubber tube and a sleeve knitted with a chemical fiber covering the tube. The rubber tube expanded; the sleeve deformed; and the artificial muscle produced force and displacement along the direction of contraction when air pressure was applied. While its working principle and structure were identical to those of McKibben's artificial muscle [6], we implemented miniaturization using a different material and by devising a distinct fabrication process [7]. The muscle was extremely light, flexible, and thinner compared to the conventional McKibben-type artificial muscle. These features can help develop musculoskeletal robots [8] and robot arms [9].

B. *Muscle Textiles*

The muscle textile is a kind of active textile constituted by multiple soft thin muscles with the advantage of yielding a high power output while securing flexibility as it is bundled (Fig. 3). The woven muscle textile developed by Ohno et al. [10] delivered a large force, was flexible, and had a shape with integrity (Fig. 4). Delivering a large force and being flexible at the same time are difficult for traditional actuators. A muscle textile in plaits with the soft thin muscles has been developed [11]. These ideas were applied, and our support suit was developed.

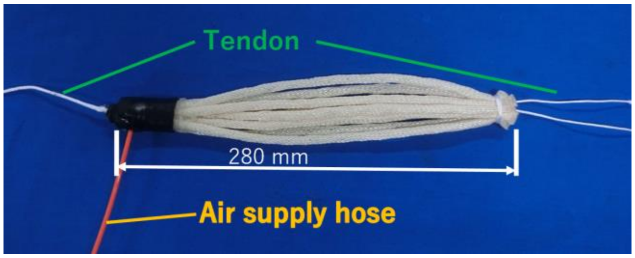

Figure 3. Bundle-type muscle bundling: 10 4.0 mm soft thin muscles.

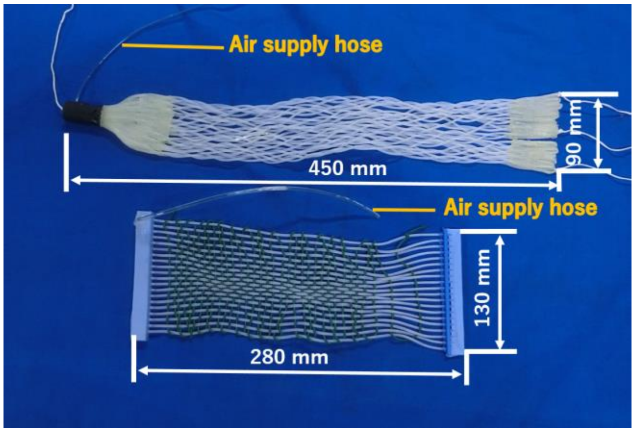

Figure 4. Muscle textile (plait type: upper; woven type: lower).

TABLE I. PARAMETERS USED TO ANALYZE THE OVERLAP EFFECT OF THE MUSCLE

Parameter	Value
Initial length of muscle:l_0	500 mm
Initial diameter of muscle:d_0	4.5 mm
Inflated diameter of muscle:d	9 mm
Number of muscle: n	10
Cross angle: ϕ	15, 30,56,60°

C. *Behavior of the Overlapping Muscle Textile*

This section describes the muscle textile behavior when it overlaps. As in the support suit proposed in this study, when the muscle textile is installed to overlap, its layers can interfere with one another during operation. Consider the drive behavior while layers of two muscle textiles overlap with each other. For the sake of simplicity, we assume that the muscle textile does not sag by neglecting the effect of the artificial muscle end. Consider the effect of interference on the muscle textile passing over the path of another (Fig. 6). When the path of the upper part of the muscle textile is changed by

TABLE II. Purpose, Arrangement, And Lenghth Of Muscle Textiles

Textile Name	Support	Origin	Insertion	Length [m]
MT1	Elbow extension, Shoulder extension	Shoulder	Elbow	0.16
MT2	Elbow extension, Horizontal shoulder extension	Shoulder	Wrist	0.42
MT3	Elbow flexion, Shoulder flexion	Shoulder	Elbow	0.15
MT4	Elbow flexion, Horizontal shoulder flexion	Shoulder	Wrist	0.34
MT5	Shoulder flexion	Knee	Elbow	0.80
MT6	Shoulder horizontal flexion	Left shoulder	Right shoulder	0.34

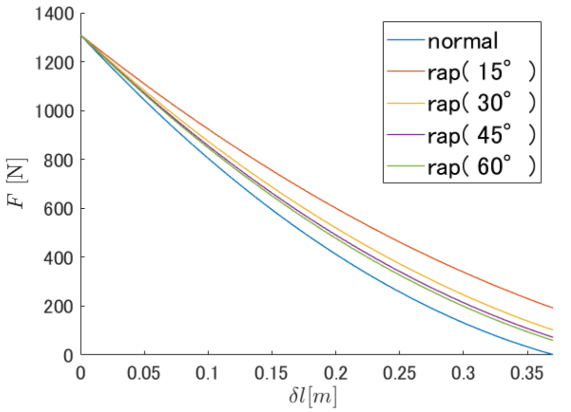

Figure 5. Relationship F-$\delta l'$ depending on the presence/absence of overlap.

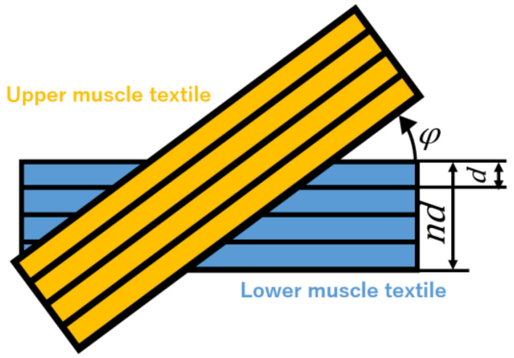

Figure 6. Schematic diagram of the overlapping muscle textile.

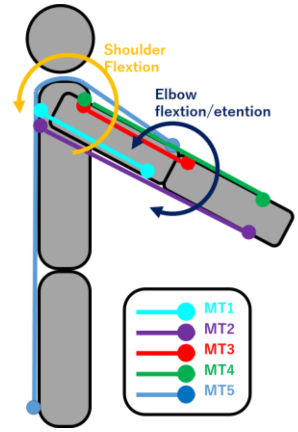

Figure 6. Conceptual diagram of the soft suit.

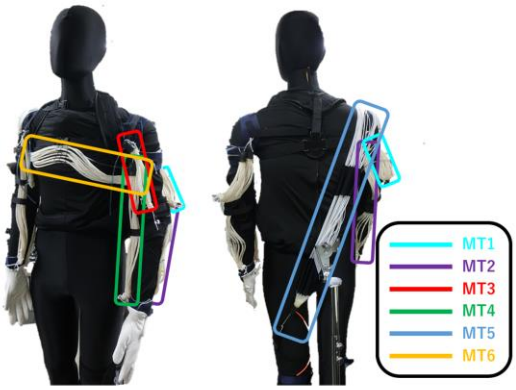

Figure 7. Front view (left) and back view (right) of the soft suit.

the expansion of its lower piece, a substantial change in the path length can be observed in the former. The influence on the contraction ratio of the upper muscle textile can be represented by the following expression:

$$\varepsilon' = \frac{l}{l_0' + \delta l'} \qquad (1)$$

where l is the length of the artificial muscle; l_0' is the initial length of the artificial muscle; and $\delta l'$ is the substantial initial length associated with the path being changed by the dilated artificial muscle. $\delta l'$ is guided by the radial change because of the artificial muscle expansion. $\delta l'$ can be expressed as follows assuming that the angle between the artificial muscles is ϕ:

$$\delta l' = n\frac{d - d_0}{\sin \phi} \qquad (2)$$

where N is the number of lower artificial muscles; d is the diameter of the artificial muscle at the time of expansion; and d_0 is the diameter of the artificial muscle in its initial state. The relationship between the force generated by the artificial muscle passing through the overhanging path and the shrinkage ratio is then derived as follows:

$$F = f(\varepsilon, P) \qquad (3)$$

where P is applied pressure. The expression from Kagawa of a model for artificial muscles [12] is then given as:

$$F = f(\varepsilon', P') = \alpha(1 - \varepsilon')^2 P' + \beta P' + \gamma \qquad (4)$$

where α, β, and γ are experimentally derived coefficients, and $\alpha = 3.5 \times 10^{-4}$ m^2, $\beta = -2.32 \times 10^{-4}$ m^2 , and $\gamma = 4.63 \times 10^{-3}$ N. Fig. 5 shows the difference between the outputs when considering the effect of the interference of the route.

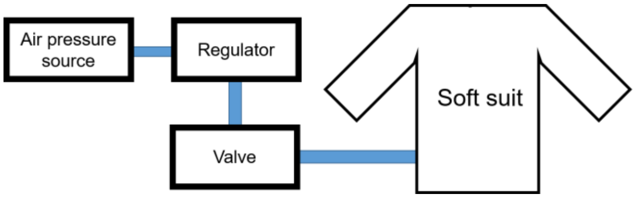

Figure 9. Control system of the soft suits.

Table I lists the parameters used in the analysis. The displacement magnitude was increased by considering the effect of the path interference. The assistance model of the behavior when the muscle textiles overlap is described in detail in the next section.

III. SUIT DESIGNS

A. Design

The soft suit was designed to support shoulder flexion, horizontal flexion, and elbow flexion and extension, and can be divided into two parts: one that performs the flexion motions of the shoulder and one that performs the other movements. In other words, this suit was constructed by joining two functional parts. The suit weighed approximately 2 kg and consisted of 11 muscle textiles. Fig. 8 shows a prototype of the suit, while Fig. 7 presents its conceptual diagram. Table II lists the points of attachment of the artificial muscles.

The part designed for shoulder flexion was further composed of three parts: knee orthosis, elbow orthosis, and muscle textiles. The combined mass of all the components was 860 g. The muscle textile was attached to connect from the knee through the shoulder to the elbow orthosis. A muscle textile made by sewing 50 soft thin muscles onto a flexible fabric with a diameter of 1.8 mm and a length of 0.8 m was used. Table II summarizes the purpose and the arrangement of the muscle textiles in five lengths of 10 bundles of 4 mm artificial muscles. These ends of the muscle textiles were attached to the gloves, elbow orthosis, and shoulder-type orthosis. This part weighed 1.2 kg.

B. Control System

The control system was a simple system consisting of a pneumatic source, valves, a regulator, and a support suit. Sensors were not needed because it aimed to balance the posture shifting. The idea was to shift the balance of force when relaxing. The muscle textile was compliant; hence, wearers could change the angle of the arm even if they shifted posture to a certain extent. Moreover, a follow-up control to the angle made by the arm was not used; thus, utilizing angle sensors or analog valves was not necessary. Furthermore, if air pressure is applied to the support suit prior to operation, pressure does not need to change or be released until after the given task has been completed. Thus, the pressure source can be separated from the control system after air pressure is applied. As a result, a modular and miniaturized pneumatic system was easily implemented, and the assistance suit operation became easier.

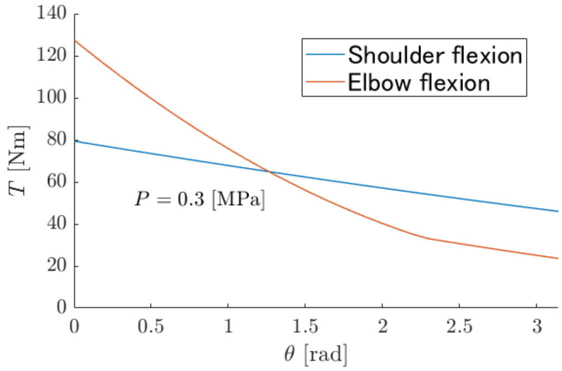

Figure 10. Assistance torque in shoulder flexion and elbow flexion from the results of analysis

C. Analytical Model

The equation for the relationship between the angle of the arm θ and the torque T was given below. The contraction ratio ε was derived from the rotation angle θ of the arm and the contraction force F of the artificial muscle. Kagawa's formula was used to model the artificial muscle [12]:

$$\varepsilon = \frac{r\theta}{l_0} \tag{5}$$

$$F = f(\varepsilon, P) \tag{6}$$

where r is the center of rotation of the given body part. The torque was derived at an angle θ using the following equation:

$$T = Fr \tag{7}$$

The muscle textile overlap can be expressed as follows using F' obtained from Eq. (3):

$$T = F'r \tag{8}$$

As described in Section II.C, the contraction displacement of the artificial muscle increased when pieces of the muscle textile overlapped with each other. When this observation was applied to this model, the supportable angle evidently increased in the case of overlapping. Hence, when the elbow was flexed, two pieces of textile were driven while overlapping. Thus, the effect of overlapping should be considered. Fig. 10 shows the assist torque in the flexion of the shoulder and the flexion of the elbow obtained from this analysis result. R = 0.06 m expresses the center of rotation of the shoulder joint, while 0.047 m presents the center of rotation of the elbow joint.

IV. EVALUATION

A. Evaluation Method

This section describes the three methods used to test the proposed soft suit. We tested the performance in terms of shifting the BPB using the pressure–angle relationship, the effect of the reduction on the burden on the muscles using EMG, and the effect of the support overall using a stabilometer. The height and the weight of the 22 year-old male subject were 1.72 m and 50 kg, respectively.

1) Pressure–angle relationship

The relationship between the pressure applied and the angle between the arm and the gravity direction was measured to evaluate the ability of the soft suit to shift the balancing posture of the body. We measured the shoulder flexion as a typical motion. At the time of relaxation, the angle of the arm when changing the applied pressure was measured using the following procedure (Fig. 11):

1) Start the measurement.
2) Maintain the arm in a relaxed state.
3) Increase the applied pressure on the artificial muscle from 0 MPa to 0.4 MPa over 40 s.
4) Reduce the applied pressure on the artificial muscle from 0.4 MPa to 0 MPa over 40 s.
5) End the measurement.

The small radio multi-function sensor, TSND121, with a built-in acceleration/angular velocity sensor and a geomagnetic sensor was used to measure the angle of the arm. The pressure was controlled by an electropneumatic regulator (EVT500-0-E2-3G).

2) EMG

We investigated the effect of the soft suit in reducing the burden on the wearer's muscles through an EMG test. We also measured the surface myoelectric potential for a posture where the elbow was extended straight (i.e., where the contractile force of the artificial muscle was the largest). With a weight of 1.25 kg held, the position was maintained for 30 s, and the surface myoelectric potential was measured. The values at the application of air pressure and without it were then compared. In the test, pressure was applied to two muscle textiles related to the elbow flexion. Electrodes were attached to the brachioradialis muscle, the biceps brachii muscle, and the triceps brachiius muscle corresponding to the antagonist muscle of the biceps brachialis muscle. FREE EMG 1000 was used as surface electromyography.

3) Body sway

We investigated the body sway to evaluate the effect of the support provided by the soft suit as a whole. The stabilometer is a device used to detect the center of pressure of the subject. It calculates the balance function of a person and primarily used as a medical equipment. The fatigue of the lower body and the upper limbs extends the length of trajectory of the body sway. Imamura [13] evaluated lumbar-supportive orthosis using a stabilometer. In the present study, the effect of the support for the upper limbs provided by the proposed suit was evaluated using a stabilometer, which can detect trembling caused by arm fatigue. The length of the trajectory of the body sway increased when the load applied to the arm was heavy.

The center of pressure was measured while maintaining a predetermined position to assess the influence of air pressure on the center of the pressure while maintaining posture. As shown in Fig. 16, a weight of 4 kg was held for 30 s with the angle of the elbow fixed at 90°. The center of pressure was then measured for 30 s. This experiment was conducted with and without the application of pneumatic pressure. Air pressure was applied to three muscle textiles related to posture maintenance. A Wii Balance Board was used as a stabilometer. The data acquisition software, FitTri [14], was partially modified and used as well.

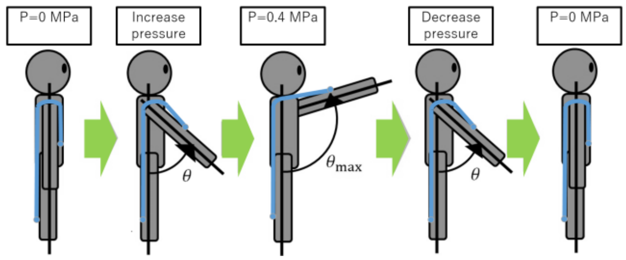

Figure 11. Balancing point shifting examination

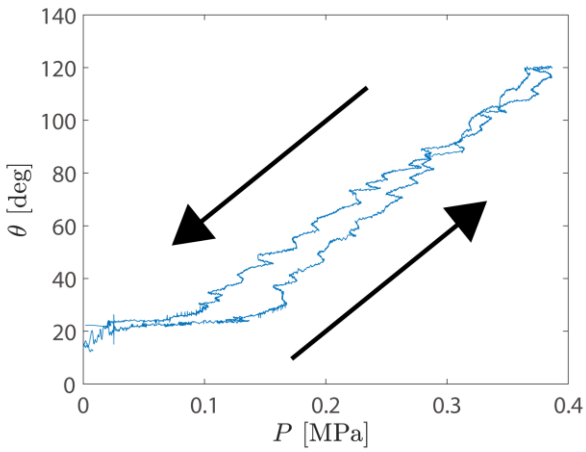

Figure 12. Results of the balancing shifting posture examination

TABLE III. iEMG OF EACH MUSCLE SET

	iEMG ± SD (without air) [mV]	iEMG ± SD (0.4 MPa) [mV]
Biceps brachii	10.6 ± 1.8	7.07 ± 1.3
Brachioradialis	6.86 ± 1.5	6.80 ± 0.2
Triceps brachii	3.19 ± 0.9	4.92 ± 1.1

TABLE IV. TOTAL TRAJECTORY OF THE BODY SWAY

L ± SD (without air) [mm]	67.9 ± 11.9
L ± SD (0.4 MPa) [mm]	64.3 ± 11.9

B. Examining the Shift of the Balancing Posture

The capability of the soft suit to shift the balancing posture of the body was tested in this fitting. As a typical motion, the relationship between the pressure and the angle between the arm and the direction of gravity was evaluated for the shoulder flexion.

Fig. 12 shows the relationship between the pressure and the angle obtained by the subjective experiment. We succeeded in shifting the balancing posture until approximately 120° at a 0.4 MPa pressure. The result showed that the soft suit can sufficiently compensate for its own weight.

C. Examining the Effect of Support

We evaluated the effect of the burden reduction on the muscles by EMG. For the examination, the subject held a weight with the elbow straightened, and this posture was maintained. At this time, the myopotentials for the following

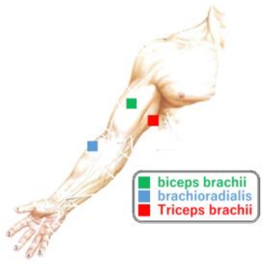

Figure 13. Locations of the EMG sensor [15].

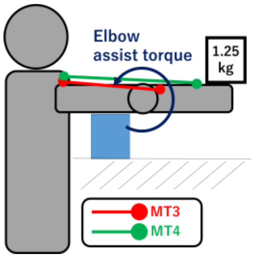

Figure 14. EMG examination.

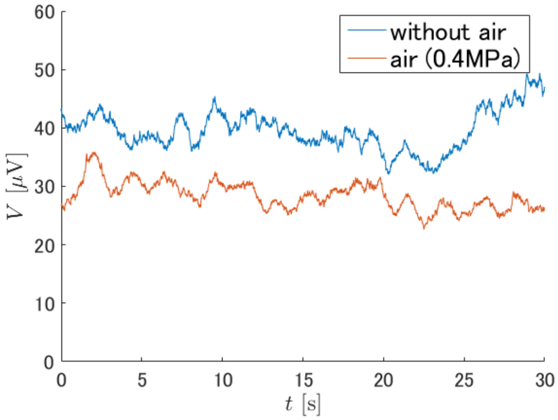

Figure 15. Rectified myoelectric potential of the brachii muscles (3 s simple average).

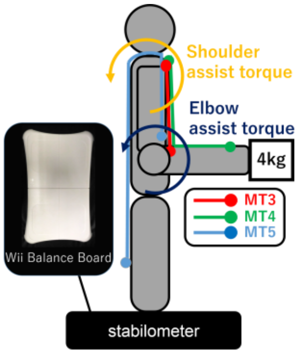

Figure 16. Body sway examination.

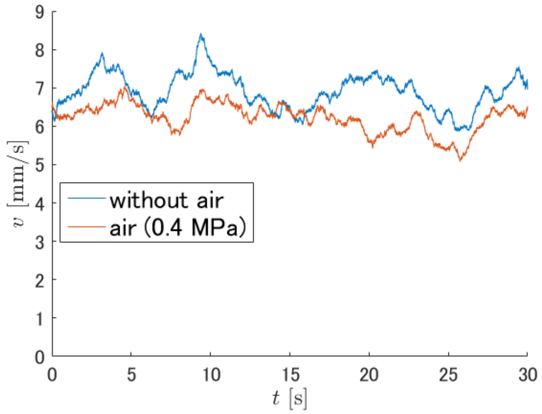

Figure 17. Changing speed of the total trajectory (3 s simple moving average).

muscles were measured: brachioradialis muscle, biceps brachii muscle, and triceps brachiius muscle, which was the antagonist muscle. Fig. 15 and Table III show the results. The integrated EMG (iEMG) decreased by approximately 33% in the biceps brachialis muscle when air pressure was applied to the soft suit. Fig. 15 illustrates that the myoelectric potential of the biceps brachii muscle decreased, suggesting that these muscles were supported by the soft suit.

We then measured the body sway to assess the effect of the soft suit on the entire arm in the given posture. The movement of the center of pressure of the subject was measured holding a weight of 4 kg for 30 s while fixing the angle of the elbow at 90°. Table IV and Fig. 17 present the results. The locus length decreased by 5% when air pressure was applied. Fig. 17 shows that the speed of the overall trajectory decreased when pneumatic pressure was applied. In conclusion, the soft suit can reduce the burden on the entire arm.

In this section, we verified the performance of the soft suit in terms of a reduction in the myoelectric potential of the brachioradialis muscles and the biceps brachii muscles and the suppression of the body sway by examining the EMG and the body sway.

V. CONCLUSION

In this work, we designed and tested a support suit by employing two novel concepts: muscle textile and shifting the balancing posture of the body. We succeeded in designing an expandable, flexible 2 kg body suit using the former. We also devised a simple control system that modularizes and miniaturizes the pneumatic system design by introducing the shifting of the balancing posture. The experiments performed on our suit confirmed its ability to shift the balancing posture for the shoulder flexion. The EMG measurements also confirmed a decrease in the myoelectric potential in the biceps brachii muscle and the brachioradialis muscle during the isometric elbow contraction. We confirmed that the suit can suppress body sway by measuring the body sway. The results also confirmed that a soft suit weighing 2 kg attained a self-weight compensation of up to 120° forward, a reduction of 33% in the iEMG in the brachialis muscle, and a suppression of 5% in the body sway. We showed that the concepts of muscle textile and shifting the balancing posture can be used to develop soft and light-support suits. In a future work, we will further extend the suit to other postures and optimize the muscle textile to improve the assistive force and area. We will also consider its on-site operation.

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