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Assistance of the elbow flexion motion on the active elbow orthosis using muscular stiffness force feedback †

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Abstract

An elbow orthosis with pneumatic artificial muscles has been developed to assist and enhance upper limbs movements and has been examined for effectiveness. The effectiveness of the elbow orthosis was examined by comparing muscular activities during alternate dumbbell curl motion wearing and without wearing the orthosis. The subjects participating in the experiment were young adults in their twenties. The subjects were instructed to perform a dumbbell curl motion in a sitting position with and without wearing an orthosis in turn, and a dynamometer was used to measure elbow joint torque in isokinetic mode. The measurements were done with four various dumbbell loads: 0, 1, 3, and 5 kg. We examined the effectiveness of the elbow orthosis in two control methods. First, the orthosis was pneumatically actuated and controlled in the passive control mode. Then, it was controlled in the active control mode using the muscular stiffness force of the muscle that is measured from a force sensor through a cDAQ-9172 board. For the analysis of muscular power, the muscular activities of the subject were measured during alternate dumbbell curl motion using MP150 (BIOPAC Systems, Inc.). The muscles of interest were biceps brachii muscle, triceps brachii muscle, brachioradialis muscle, and flexor carpi ulnaris muscle in the upper limbs of the right side. The elbow joint torque was measured during elbow flexion motion using a dynamometer at 60° per second for isokinetic strength. The experimental result showed that the muscular activities wearing the elbow orthosis were reduced and elbow joint torque wearing the elbow orthosis was higher because of the assist of the orthosis. As a result of this experiment, the effectiveness of the developed elbow orthosis was confirmed and the level of assistance was quantified. With this, we confirmed the effectiveness of the developed elbow orthosis.

Keywords: Muscular stiffness force feedback; Active elbow orthosis; Elbow flexion motion

1. Introduction

Due to traffic accidents or industrial accidents, the number of people who present with upper limb paralysis is persistently increasing. Most cases of upper limb paralysis are characterized by a loss of motor function, and the corresponding patients present with such abnormal symptoms as weakness of muscular strength, a loss of the sensory functions and abnormal functions of the autonomic nervous system. For the rehabilitation treatment of these symptoms, the rehabilitation training using an orthosis maintains and then improves the activities of daily lives as well as the prevention of contracture of the upper limb joint and the decreased stiffness. Due to the impaired functions of the musculoskeletal system, the use of an orthosis that can support the weakened muscular strength has been increasing. Through muscular strength training, instruments for enhancing muscular tolerance have also been developed. By supporting muscular strength and thereby raising the activities of patients with upper limb paralysis or elderly people whose motor sensory functions are limited, the functions of daily lives can be improved. By increasing such functions of daily lives as the exercise or travel and leisure activity, the elderly or those with disability can maintain independent lives. Besides, it enables these people to enjoy their lives and to improve their quality of life.

The elbow joint which applies to the elbow orthosis is the middle joint between the shoulder joint and the hand, which induces the extension and shortening of the upper extremities. The elbow joint is composed to form a stable hand structure along with the muscular tissue. Many muscles which act on the brachial joint and shoulder joint pass the elbow joint and endow it with stability. Furthermore, it enhances the functions of the hand. When these functions of the elbow joint are lost or weakened, the use of an elbow orthosis is mandatory.

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As the recovery technology of motor function about elbow joint, studies about orthosis for the muscular motor have been conducted by many researchers in such a manner as to make it possible to perform the independent motion. For the exoskeleton muscular orthosis, patients' own muscular strength or external dynamic force was used. Otherwise, upper limb orthosis of hybrid motor type for which two types were used have been developed. The operation methods which are used are also diverse. Most of the exoskeleton upper limb orthoses use a servo motor actuator or oil and air pressure actuator. In most cases for which an electrical motor is used [1, 2], there are such disadvantages as the complexity of operation circuit, the difficulty of mobility and the increased weight of the instrument. Jacob developed an exoskeleton system that can assist based on the muscle signal [3]. The exoskeleton upper limb orthosis is operated using a fuzzy-nerve method in an effort to support the movement of elbow joint in humans [4]. The artificial intelligence orthosis was developed for elbow joint (Intelligent orthosis [IO]) [5]. The glove-type finger system for assisting the manual operation was developed by the Rehabilitation Institute from Japan [6].

Recent studies have also been conducted extensively to examine exoskeleton dynamic orthosis, and these include rehabilitation orthosis for patients with muscular disease and muscular strength amplifier for soldiers who lift heavy military equipments [7, 8]. The operation methods that are used are also diverse. In the HAL (hydride assistive leg) [9, 10], the servo motor actuator is chosen for most of the exoskeleton dynamic orthosis. An exoskeleton dynamic orthosis using oil and air actuator for nurses was developed [11]. As described here, ongoing studies about an orthosis for the muscular strength in the upper limbs are being conducted. With the use of a heavy exoskeleton type based on oil pressure, air pressure operator and a motor, however, the energy excess and muscular fatigue are reduced. There is a disadvantage in that the degree of validity is relatively lower. To date, an analysis of the effectiveness and characteristics of orthosis for the muscular strength in the upper limbs has been performed to an insufficient extent.

In the current paper, the elbow orthosis for upper limbs of a light wearing exoskeleton type was developed. In young adults, when the alternate dumbbell curl (ADC) motion was performed, the characteristics of the muscular strength for upper limbs depending on the use of orthosis were assessed. When an isokinetic movement using the dynamometer was performed, the characteristics of elbow joint torque were also assessed. Thus, attempts were made to evaluate the efficiency of movement assistance performed by the upper limbs orthosis.

2. System constituents

2.1 Elbow orthosis

Fig. 1 shows the basic frame of the elbow orthosis attached to the artificial pneumatic muscle. The elbow orthosis was manufactured as a tool for supporting the movement of upper limbs. It was also manufactured by attaching the artificial pneumatic muscle which plays a role as the muscles of upper limbs.

Table 1. Specification of artificial pneumatic muscle.

Diameter	20 mm
Length	210 mm
Weight	40 g
Pull (0.35 MPa)	12 kg
Max pull	20 kg

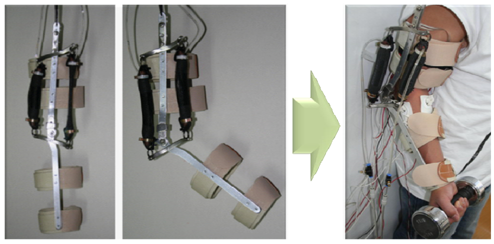


Fig. 1. Apparatus of the subject using elbow orthosis with artificial pneumatic muscle.

The artificial pneumatic muscle, which was used in the current study and had a small, light property, is a product which was manufactured by *Shadow Robot in the UK*. It is operated softly and naturally like biologically real muscle. Its advantage is that it is easily controlled. The artificial pneumatic muscle is a structure where a rubber tube is surrounded by a highly strong plastic network. If the air pressure is raised, the muscles are contracted. But if the air pressure is lowered, the muscles are relaxed. Thus, the operation is done in a similar manner to human movements. The artificial pneumatic muscle has a weight-to-power ratio of 400 : 1, and this is greater than 16 : 1 seen in a general type of pneumatic cylinder or direct current (DC) motor. It is operated by compressed air within a range of 0-70 psi (0-0.5Mpa). In the interior side of an artificial pneumatic muscle, there is a rubber tube. The exterior part of the tube is composed of the structures surrounded by a plastic network.

Table 1 represents the specification of the artificial pneumatic muscle which was used in an elbow orthosis. The artificial pneumatic muscle which was used plays a role in supporting the biceps brachii and the triceps brachii muscles. For the free movement of the upper limbs and the weight-lowering effects, the supporting structure was prepared for the external part only. To make sure that it can be used with no respect to the physique, the wrist part was composed to have a band form. For the attachment of the artificial pneumatic muscle, the jig was manufactured. Thus, the arm was connected to the forearm.

2.2 Passive manipulation of the elbow orthosis

In the current study, to manipulate the artificial pneumatic muscle which was installed in an elbow orthosis, a solenoid valve (SY3520-VLZ-C6-F2, SMC Korea Inc.) was used. To control two artificial pneumatic muscles of the elbow orthosis, the solenoid valve was an automatic 5-port valve. With the use of a pressure center mode, the valve was directly converted

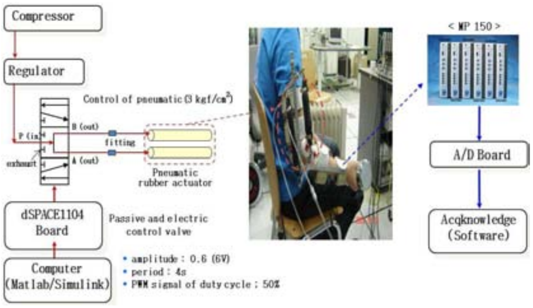


Fig. 2. Block diagram of passive control of the elbow orthosis.

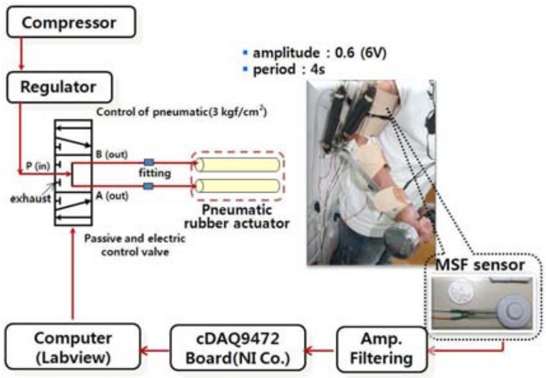


Fig. 3. Block diagram of active control of the elbow orthosis.

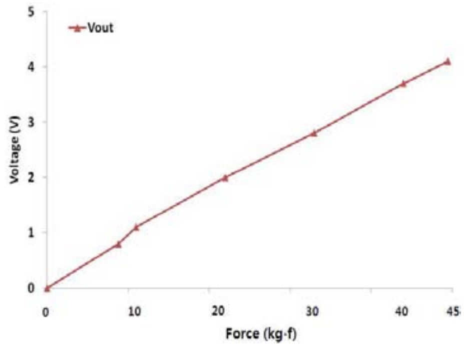


Fig. 4. Calibration of muscular stiffness force sensor.

using a coil. The air pressure was introduced to one of the two actuators. In the remaining one actuator, the air pressure was exported and then removed. The valve, which is operated by the authorization of DC 6V, has lead lines placed externally on both sides. Using the computer, the control voltage was authorized. Fig. 2 represents the block diagram illustrating the method for controlling the solenoid valve using two artificial pneumatic muscles installed in the elbow orthosis. When the orthosis was implanted, the pressure exerted to the artificial pneumatic muscle of the orthosis was 0.294 MPa. For the control input, a dSPACE1104 control board and Matlab/Simulink (The MathWorks Inc.) were used. The input voltage to valve the valve was generated using a simulator which was reconstructed in a computer. This is transmitted to the solenoid valve through the dSPACE 1104 control board. By operating the valve, the artificial pneumatic muscle is operated. At this time, the period was 4 seconds and the duty cycle of pulse width modulation (PWM) signals was set at 50%. With the action of the artificial pneumatic muscle, the elbow orthosis can perform the basic movements of muscles, including flexion and extension.

When the subjects perform ADC motion, the signals of muscles of the upper limbs authorize the analogue signals to the electromyographic modules. Muscular signals are converted to digital signals via analog-to-digital (A/D) converter. Through signal processing, they are authorized to the computer.

2.3 Active feedback control of the elbow orthosis

Methods for actively controlling based on the muscular stiffness force signal are shown in Fig. 3. Controlling was done using a solenoid valve of the artificial pneumatic muscle which was placed in the elbow orthosis. The air pressure generated in the compressor is controlled by a regulator. This air pressure is authorized to the artificial pneumatic muscle through a solenoid valve. The block diagram is represented.

At this time, the solenoid valve controlling the air pressure which is authorized to an artificial pneumatic muscle is operated by measuring the muscular signals of biceps brachii which are obtained from the muscular stiffness force sensor. Methods for supporting the exercise of elbow orthosis include to measure the muscular stiffness force signal of biceps brachii, which is first generated when flexion of the elbow joint occurs and to transmit it as a voltage authorization signal of solenoid valve. Using a commercial program, LabVIEW program (National Instruments Co.), we enabled a program where the voltage signals are received from a muscular stiffness force sensor and then transmitted to a solenoid valve. A voltage signal which was enabled by LabVIEW is authorized to have 6V by which a solenoid valve is operated using an output module of cDAQ-9472 board (National Instruments Co.). The artificial pneumatic muscle, which is operated using this signal, supported the flexion movement of the elbow joint.

2.4 Sensor for measuring the muscular stiffness force

To measure the muscular stiffness force signal, the muscular stiffness force (MSF) sensor was prepared [12]. The degree was measured at which certain types of muscles are stiffened depending on the movement and thereby controlled an orthosis for patients with disability [13]. Also in the current manuscript, using the degree of muscular stiffness occurring when the muscles contract depending on the movement, elbow orthosis was controlled.

As the system measuring the general conditions of muscles, an EMG method where the measurement is performed using an electromyogram (EMG) was attached on the skin surface. Because the action potential is mild and then subject to noise, however, such analytical methods as amplification or filter analysis are difficult. A cream which is used to attach an electrode gives discomfort to users. It is therefore inappropriate for a wearing type of operating orthosis. Accordingly in the

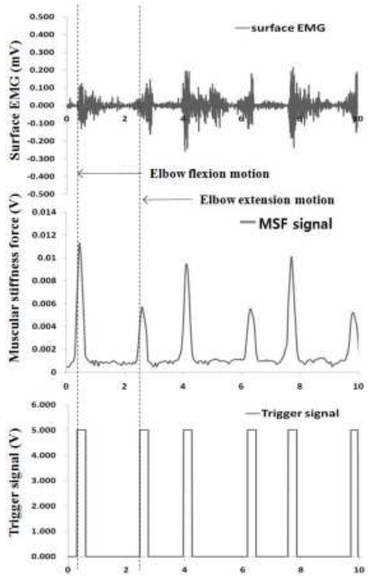


Fig. 5. Synchronization of surface electromyography muscular stiffness force signal.

current study, the signals indicating the magnitude of muscular strength whose status can easily be detected were used.

In these methods, a piezoelectric resistive pressure sensor (FlexiForce, A201, Tekscan Inc., USA) is used. During the ADC motion of the elbow joint, the contraction pressure due to the muscular activity is measured. At this time, a piezoelectric resistive pressure sensor is attached to a calf band and then closely adhered to the surface of muscles which are measured. As compared with the methods for measuring the action potential of muscles, this is not affected by noise. It is also unnecessary to apply a specific type of cream. Accordingly, it is appropriate for a wearing type of orthosis.

Fig. 5 is a graph which was plotted following the comparative measurement of surface EMG (sEMG) of biceps brachii muscle and the magnitude of its muscular strength during the flexion of the elbow joint. The first picture represents the surface EMG of biceps brachii muscle and the third one represents a trigger signal which is generated when the signals indicating the magnitude of muscular stiffness force exceeded the threshold values in the second picture. As shown in these figures, only when the signals indicating the magnitude of muscular stiffness force of biceps brachii muscle exceeded a certain degree of power (the threshold values) in all the subjects, the air pressure was input to an artificial pneumatic muscle with the action of a solenoid valve. According to this, the flexion motion of elbow joint is supported. Thus with the use of a sensor measuring the magnitude of muscular stiffness force which was prepared for the current study, it was confirmed that an elbow orthosis could receive an active control.

3. Experimental methods

To examine the characteristics of muscular strength of the upper limbs, surface muscular activities and muscular fatigues of muscles were measured relative to the elbow flexion motion in wearing the orthosis and not wearing it. And maximal isokinetic torque of elbow joint during isokinetic flexion motion in elbow joint was measured in wearing and not wearing it.

3.1 The measurement of muscular activities of the upper limbs

Surface muscular activities of the muscle were measured through electromyography (EMG). EMG signals are an electrical potential which is generated by the migration of ions because of the contraction and relaxation of muscles. EMG measurement was done with the use of MP150 (BIOPAC Systems, Inc.). Data was collected at 1,024 samples per seconds. Measured muscles for the muscular activities include biceps brachii muscle (BB), triceps brachii muscle (TB), brachioradialis muscle (Bo) and flexor carpi ulnaris muscle (FCU). In the muscular activities which were measured, the degree of muscular activity was evaluated through an analysis of the frequency spectrum. The magnitude of muscular activities was analyzed using the power spectrum, which is obtained with the use of a fast Fourier transform (FFT) method.

Muscular fatigue is referred to as the finding that muscular fatigue is caused and pain is produced when the muscles in the specific areas are persistently used. This degree of muscular fatigue appears through an analysis of the frequency signals emitted from EMG, which is characterized by the transition of the central area of EMG frequency to a low-frequency area. Accordingly in the current study, a total of 40 seconds were divided into four parts at a 10-sec interval (part 1-4). Then, the median frequency was obtained for each part. Thus, during a total of experimental times, the trends about muscular fatigue were examined.

3.2 The measurement of the maximal torque of elbow joint depending on the isokinetic movement

An isokentic exercise is the movement where the fixed velocity is maintained by altering the resistance depending on the exerted torque, for which a sum of total forces is measured depending on the isokinetic movement. It has been extensively used for studies about the training methods for improving muscular strength, explosive muscular strength and tolerance and as a measure for making a diagnosis and treatment of the effects of exercise. An exercise loading velocity which is associated with the isokinetic muscle training is the most crucial parameter [14, 15].

The isokinetic movement provides the loading of the maximal muscular strength over the total movement range as compared with other movements. There is a lower possibility that an injury occurs due to the overloading to subjects' muscular system. Due to various types of the velocity provided by isokinetic equipment, an analytical measurement was performed with the use of a muscular strength loading measurement system (Biodex Medical System, Inc.) which can effec-

Table 2. Experimental condition of maximum torque on isokinetic motion of elbow flexion.

Away	Extension
Toward	Flexion
Ready position	Full flexion
Dynamometer orientation	30°
Dynamometer tilt	0°
Seat orientation	0°

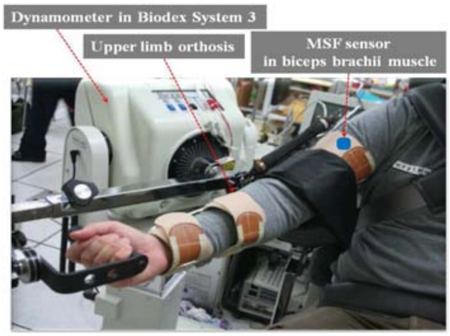


Fig. 6. Apparatus of isokinetic muscular activities of elbow flexion using elbow orthosis.

tively be used for both a fast twitch and a slow twitch), a measuring device for isokinetic muscular strength training. In the current study, the muscular strength was measured at a loading velocity for the elbow joint of 60˚/sec.

Fig. 6 illustrates the measurement of muscular strength during the isokinetic movement depending on the action of elbow orthosis to which an artificial pneumatic muscle was implanted. The basic experimental conditions for measuring the maximal torque during the isokinetic flexion of elbow joint are represented in Table 2. The rotational angle of the main body of dynamometer was fixed at 30˚. The initial slope angle was set at 0˚.

Measurement methods were as follows:

(1) Subjects were placed on equipment for measuring the amount of loading of muscular strength exercise.

(2) The central point of the elbow joint was set to be matched to a rotational axis of a dynamometer.

(3) During the isokinetic flexion of the elbow joint, to make sure that no forces should be exerted to other body areas, the chest and femoral area were fixed.

(4) Subjects were allowed to move within a range of 0˚ - 60˚, whose movement was initiated with a focus on the elbow joint. At this time, the ROM (range of motion) which does not deviate from < 0˚ or > 60˚ is induced.

(5) To enhance subjects' adaptability to the equipment during the measurement, the preliminary movement was performed three times. To do this, ten healthy males were selected as subjects. In these subjects, mean weight was 72.2 kg (63-80 kg).

(6) The experiment was performed a total of three times per each patient, for which subjects underwent a resting period for approximately ten minutes following a session of the experiment.

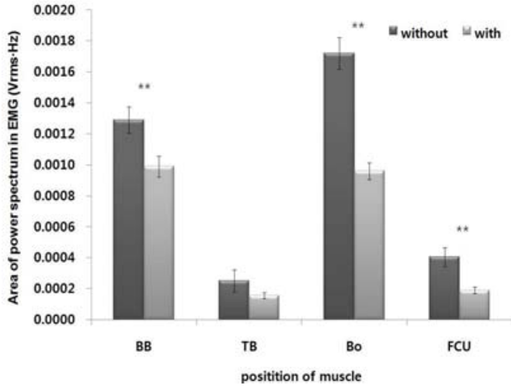


Fig. 7. Characteristics of upper limb muscular activity using elbow orthosis on ADC motion.

3.3 Statistical analysis

All the tasks and statistical analysis were performed using SPSS (v.12) program, for which the mean and standard deviation were calculated. When the support was made using a control, for a comparison of differences in the EMG of lower extremities and the flexion torque of the elbow joint, a paired t-test was used. To demonstrate the difference in the amount of changes, a t-test was performed. A level of statistical significance was set at $*p<0.05$ and $**p<0.001$.

4. Results and discussion

4.1 The characteristics of muscular activities of the upper limbs depending on passive control

4.1.1 The characteristics of muscular activity depending on the location of muscles

Muscular activities which were measured were analyzed using Acqknowledge 3.8.1, whose results were visualized on the screen. Statistical analysis was performed using SPSS 12.0 version for Windows, where the statistical significance was obtained for experimental results using a paired t-test. Statistical significance was set at $p < 0.05$.

Fig. 7 represents the characteristics of the activity of muscles in the upper limbs in wearing the orthosis during ADC movement as compared with not wearing the orthosis. (*, $p < 0.05$, **, $p < 0.01$) The horizontal axis represents the location of muscles. The vertical axis represents the area of the power spectrum which was obtained from an analysis of the muscular activity which was measured. The degree of muscular activity depending on the use of elbow orthosis was measured, and this showed that it was relatively smaller in cases in which the orthosis was used. In particular, based on the characteristics of the flexion of the elbow joint, the degree of muscular activity use showed that biceps brachii muscle and brachioradialis muscle received the assistance of muscular activity to a greater extent than triceps brachii muscle and flexor carpi ulnaris muscle during the flexion motion. In cases in which subjects used the elbow orthosis, the supporting effects were seen in approximately 23% of biceps brachii and approximately 41% of brachioradialis. These

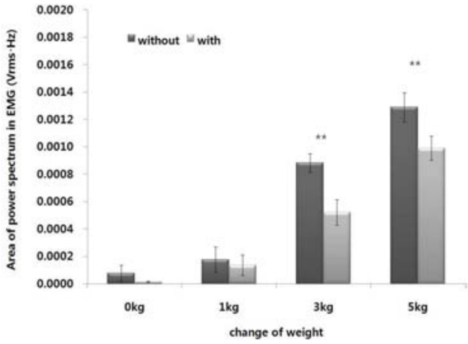


Fig. 8. Muscular activities of upper limbs according to the variation of weight on ADC motion.

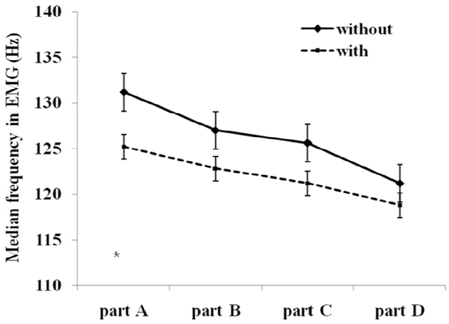


Fig. 9. Muscular fatigue analysis of the upper limbs during ADC motion (* $p<0.05$).

results indicate that an effective movement could be performed using a smaller degree of muscular activity in cases in which subjects used the elbow orthosis and received pneumatic support with an artificial pneumatic muscle.

4.1.2 The characteristics of muscular activity depending on the changes of loading

Fig. 8 represents an analysis of the muscular activity that illustrates the area of the power spectrum of biceps brachii, depending on the loading changes seen during ADC motion. The horizontal axis of the graph represents the magnitude of a loading provided during the exercise. The vertical axis represents the muscular activity (*, $p < 0.05$, **, $p < 0.01$).

In the current study, when the exercise was performed with the use of an elbow orthosis which was manufactured, the degree of muscular activity of upper limbs was measured to be relatively smaller as compared with cases in which the elbow orthosis was not used. Biceps brachii and brachioradialis were used at a relatively higher. When loads of 1kg, 3 kg and 5 kg in magnitude were authorized, biceps brachii received support from the muscular activity at a percentile value of 25%, 33% and 20%, as shown in Fig. 8. As described here, powerful support could be received effectively depending on the loads. It could therefore be inferred that the movement can be effectively performed even with a smaller degree of the muscular activity. This implies that an artificial pneumatic muscle of the elbow orthosis which was manufactured plays a role as the artificial muscle and thereby supports the muscular activities during ADC motion, which is elbow flexion motion.

4.2 Analysis of the upper limb muscular activity depending on the passive control

4.2.1 Analysis of the upper limb muscular fatigue during elbow flexion motion

Fig. 9 represents the results of the muscular fatigue during ADC motion depending on the use of the elbow orthosis. The horizontal axis is a part that was divided into four parts at a 10-sec interval during the experiment which was performed for a total of 40 seconds. The vertical axis is a value of the median frequency depicting the degree of muscular fatigue. Prior to and following the use of the elbow orthosis, an analysis of the muscular fatigue was performed at a 10-sec interval. As the time of ADC motion progressed, the value of the median frequency was reduced. These results indicate that muscular fatigue occurred due to the effects of exercise (**, $p<0.01$). The degree of muscular fatigue of triceps brachii was shown to be decreased by approximately 4% in cases in which the elbow orthosis was not used. In other cases, however, it was decreased by approximately 3.7%. The degree of muscular fatigue of brachioradialis was decreased by approximately 2.9% in cases in which the orthosis was not used. In other cases, it was decreased by approximately 2.4%. These results indicate that the movement can effectively be performed even with a smaller the muscular activities because a sufficient degree of the force through the pneumatic assist of the pneumatic actuator was exerted as compared with cases in which the previous muscular activities was used, depending on the criteria for the use of elbow orthosis muscular activities. This eventually led to a smaller degree of the muscular fatigue.

4.2.2 Analysis of the maximal torque of elbow joint during the isokinetic exercise

Fig. 10 comparatively analyzes the maximal torque of muscular strength, with the use of the dynamometer, between subjects in wearing and not wearing an orthosis. In these subjects (n=10), the experiment was performed three times and the results were averaged. Depending on the individual subject, there was a difference in the degree of support. Overall, the maximal torque was measured to be higher by 8.8% during extension and 4.3% during flexion in cases in which the orthosis was used (wearing the orthosis).

To consider the difference in muscular strength between the individual subjects, the peak torque/body weight was analyzed. Fig. 11 is the picture of the normalized maximal torque of the elbow joint in association with the weight. It could be shown that the value of maximal torque was increased to 6.1% during flexion and 3.5% during extension of ADC motion. These results indicate that the maximal torque was shown to be higher as compared with that seen in cases in which the orthosis was not used because the subjects used the elbow orthosis and thereby received support from isokinetic torque of the

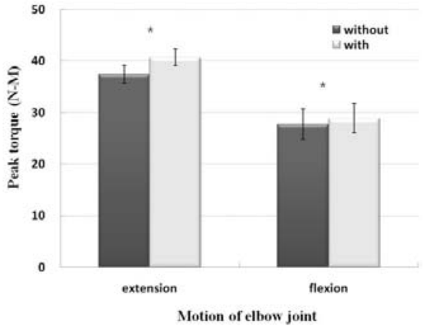


Fig. 10. Maximum peak torque with and without elbow orthosis (* p<0.05).

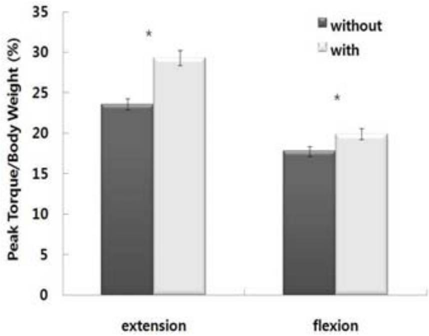


Fig. 11. Normalized maximum torque with and without elbow orthosis (* p<0.05).

elbow joint while the subjects are performing ADC motion. It is also assumed that the maximal torque for normalized weight is observed to be relatively higher.

4.3 Analysis of the upper limb muscular activity depending on the active control

4.3.1 Comparative analysis of the muscular stiffness force of biceps brachii depending on the active control

In the current study, with the use of the muscular stiffness force sensor manufactured to actively control the elbow orthosis, an MSF sensor was tested during the ADC exercise. The results are seen in Fig. 12.

Fig. 12 depicts the results of the measurement of muscular stiffness force of biceps brachii and triceps brachii using the MSF sensor when extension and flexion of the elbow joint were repeatedly performed ten times. According to this, when the flexion of elbow joint occurred, it was confirmed that the magnitude of the voltage signal on the biceps brachii muscle was observed to be relatively greater. Accordingly in the current paper, as the muscle for actively controlling the elbow orthosis, biceps brachii was selected. When the elbow orthosis was used and the ACD movement was performed, the feedback of muscular stiffness force was also performed.

4.3.2 An analysis of the muscular activities of the upper limbs depending on the active control

Fig. 13 represents the characteristics of muscular activity in

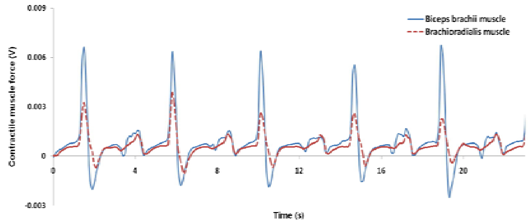


Fig. 12. Muscular stiffness force peak value in ADC motion.

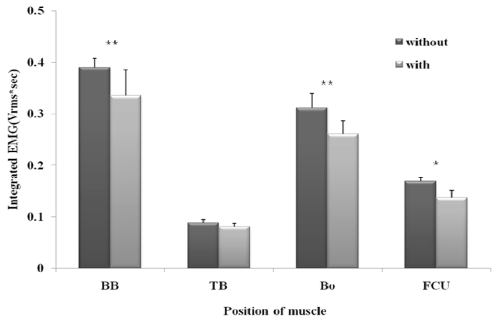


Fig. 13. Characteristics of upper limb muscular activity with and without elbow orthosis on ADC motion (*p<0.05, **p<0.001).

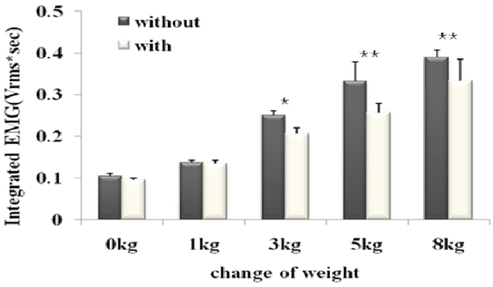
the upper limbs in applying active control and not applying it for ADC motion. The horizontal axis represents the location of muscles. The vertical axis represents IEMG which was obtained through EMG of the muscles (**p<0.01, *p<0.05).

A comparison of the presence of active control of elbow orthosis was made, and this showed that the muscles of the upper limbs were involved to a lesser extent in cases in which the ADC motion was performed following the use of active assist. In particular, based on the characteristics of elbow orthosis, the degree of muscular use was evaluated. During the flexion motion, biceps brachii muscle and brachioradialis muscle received support from the muscular activity to a greater extent as compared with triceps brachii muscle and flexor carpi ulnaris muscle. These results indicate that the movement could be performed even with a smaller degree of muscular activity in cases in which the active control was used because the force support was received according to the active control of elbow orthosis using a artificial pneumatic muscle.

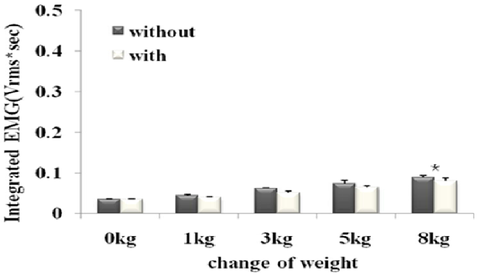
Fig. 14 illustrates the characteristics of muscular activity depending on the loading change during ADC motion (**p<0.01, *p<0.05). In Fig. 14(a), (b), (c) and (d) represent muscular activity findings of biceps brachii, triceps brachii, brachioradialis and flexor carpi ulnaris. In cases in which the active control was attempted with the use of elbow orthosis which was manufactured, the muscular activity of the upper limbs was measured to be smaller as compared with that in which no active control was attempted. When the degree of loading was increased, the effects of force support were confirmed to be relatively higher.

4.3.3 An analysis of the maximal torque of elbow joint during the isokinetic exercise based on the active control

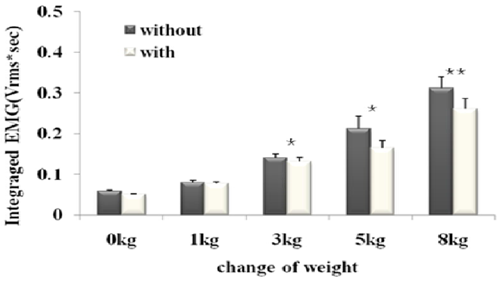
Fig. 15 comparatively analyzes the muscular strength de-



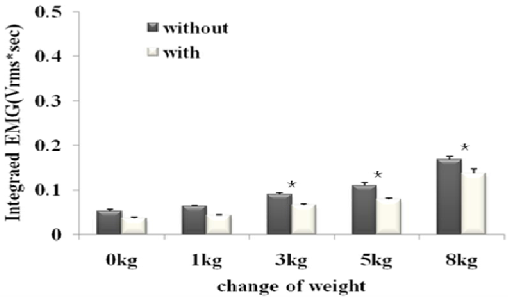
(a) Biceps brachii (BB)



(b) Triceps brachii (TB)



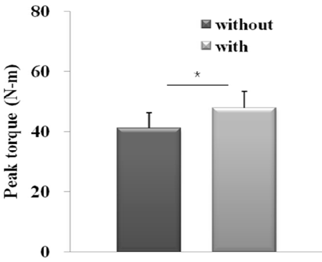
(c) Brachi oradialis (Bo)



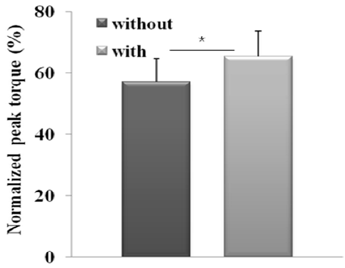
(d) Flexor carpi ulnaris (FCU)

Fig. 14. Muscular stiffness force peak value in ADC motion (*p<0.05, **p<0.001).

pending on the involvement of active control in cases in which the elbow orthosis was used based on the dynamometer (*p<0.05). In Fig. 15, (a) represents the maximum peak torque and (b) represents the normalized peak torque which was divided by the weight. In these subjects (n=10), the experiment was performed three times and the results were averaged. There is a difference in the degree of support between the individual subjects. The value of maximal torque was measured to be relatively higher during the flexion in cases in which active



(a) Maximum peak torque



(b) Normalized peak torque

Fig. 15. Muscular stiffness force peak value in ADC motion (*p<0.05).

control using the muscular stiffness force was used (Fig. 15(a)).

According to Fig. 15(b), to consider the difference in muscular strength between the individual subjects, peak torque/body weight was analyzed. This showed that the normalized maximal torque was increased during the isokinetic flexion motion of the elbow joint. These results indicate that the subjects were vulnerable to the increased power support according to the active control of elbow orthosis when the subjects performed the isokinetic flexion motion of the elbow joint. A higher degree of the value was observed as compared with cases in which no active control was attempted. Even in normalized cases, the maximal torque per weight is assumed to appear to be higher.

In Figs. 10 and 11, the increasing rate of the peak torque and normalized torque during elbow flexion motion in passive control were respectively measured by 4.3% and 3.5%. On the other hand, the increasing rate of the peak torque and normalized torque in active control were, respectively, measured by 14.29% and 12.83% in Fig. 15. The increasing rate of the isokinetic torque in active control was measured to be higher than in passive control. This was because of the pneumatic assistance of active control using the comprehending the user's intention by physiological signal.

5. Conclusions

To examine the efficiency of an elbow orthosis that was manufactured in the current study, the muscular activity about the use of the orthosis was comparatively analyzed. The elbow orthosis showed that the exercise could be performed with the use of a smaller degree of muscular activity. Moreover, it was also confirmed that more accurate assistance could be received during the active control using the muscular stiffness force signal. As described here, when the movement is performed using the elbow orthosis in association with the upper limbs, a higher degree of the force could be exerted by using the elbow orthosis. Further studies will be conducted on the elderly. Thus, the efficiency of the elbow orthosis, including the active control, should be demonstrated and the movement of upper limbs should be assisted for their daily lives.

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