

*Original Article***Utility of a wearable robot for the fingers that uses pneumatic artificial muscles for patients with post-stroke spasticity**

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**ABSTRACT**

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**Objective:** We investigated the utility of a wearable robot for the fingers that we developed using pneumatic artificial muscles for rehabilitation of patients with post-stroke spasticity.

**Methods:** Three patients with post-stroke finger spasticity underwent rehabilitation for 20 minutes a day, 5 days a week, for 3 weeks. Passive range of motion, Modified Ashworth Scale (MAS), and circumference of each finger were measured before and after training and compared.

**Results:** The range of motion and finger circumference increased when using a wearable robot. The MAS improved partially, and no exacerbation was observed.

**Conclusions:** The wearable robot we developed is useful for rehabilitation of post-stroke spasticity and may improve venous return.

**Key words:** spasticity, pneumatic artificial muscle, range-of-motion exercise, venous return

approximately 30% of patients [1]. Spasticity reduces the activities of daily living score and quality of life [2, 3]. In addition to range of motion (ROM) exercises, pharmacotherapies using baclofen or botulinum toxin type A, and electrical stimulation therapy have been recommended for rehabilitation of spasticity. Yeh et al. [4] conducted ROM exercises using a motor-driven continuous passive motion (CPM) device in patients with gastrocnemius spasticity and reported significant improvements in spasticity and ROM. Diserens et al. [5] conducted ROM exercises using a motor-driven CPM device in patients with upper limb spasticity and reported significant improvements in upper limb strength and ROM. These studies demonstrated the utility of ROM exercises using CPM devices in patients with spasticity. However, no reports have described ROM exercises using CPM devices for the treatment of patients with spasticity of the fingers. Therefore, we developed a wearable robot for the fingers using pneumatic artificial muscles that functions as a CPM device (Figure 1). In this robot, artificial muscles for flexion and extension are independently attached to each finger, and flexion and extension of the fingers are possible by alternately contracting the artificial muscles for flexion and extension. The artificial muscle for flexion is wrapped around each finger and can be attached as if tying a shoelace. One reason for setting the artificial muscle for flexion along this type of non-anatomical course is the contraction rate of the artificial muscle. The contraction rate for the artificial muscle we used was 20–25%; if the artificial muscle for flexion had been attached along an anatomical course, the muscle would have had to be extended nearly to the elbow for adequate flexion in each finger. This would have markedly increased the size of the wearable robot, which may have adversely affected the attachment. Therefore, we wrapped the artificial muscle around

**Introduction**

Spasticity is a sequela of stroke, occurring in

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**Figure 1.** The developed wearable robot. Dorsal (a), palmar (b).

The wearable robot functions with a continuous passive motion. It uses pneumatic artificial muscles.

each finger to gain muscle length, thus obtaining sufficient flexion with robot extension to near the wrist. The extension component consisted of seven artificial muscles attached to the dorsal side of the fingers. The small size and light weight of the robot are considered to be advantageous features that enable it to be used bedside or at home.

We hypothesized that performing ROM exercises for post-stroke finger spasticity using this robot would improve spasticity. The purpose of this study was to investigate the effects of ROM exercises on spasticity, ROM, and edema in finger spasticity.

### Methods

We selected three patients with post-stroke finger spasticity who had been hospitalized in an affiliated institution during the 1-year period between November 2020 and November 2021. ROM exercises were performed using the wearable robot. A before-and-after comparison was used for the study design.

Eligibility criteria were finger spasticity due to stroke, Modified Ashworth Scale (MAS)  $\geq 1$ , sufficient cognitive function to provide consent, and stable cardiopulmonary dynamics. Exclusion criteria were as follows: current pharmacotherapy for spasticity, such as baclofen or botulinum toxin type A, severe spasticity with pain when using the wearable robot, and lack of consent for performing ROM exercises using the wearable robot. Three patients met the criteria, and the breakdown was as follows: Case 1 was a 70-year-old man with spasticity of the flexor muscles of the right thumb to those of the ring finger 9 months after the onset of left thalamic hemorrhage. The degree of paralysis was Brunnstrom stage IV, and hypoesthesia was observed in the right hand. Case 2 was a 65-year-old man with spasticity of the flexor muscles of all

fingers of the right hand 10 months after the onset of left cerebral infarction, paralysis of Brunnstrom stage II, and hypoesthesia of the right fingers and forearm. Case 3 was a 74-year-old woman with spasticity of all fingers of the left hand 9 months after the onset of left cerebral infarction, with paralysis of Brunnstrom stage II, and hypoesthesia of the left thumb to the ring finger.

The ROM exercise using this wearable robot was performed for 20 minutes a day, 5 days a week, for 3 weeks. Passive ROM, MAS, and the circumference of each finger were evaluated. Passive ROM was defined as the range from maximal flexion to maximal extension and was measured using a finger goniometer. For finger circumference, the maximum circumference of each finger was measured. Measurements were made before and at the end of the training, and each evaluation item was compared before and after training. The presence of adverse events, such as pain or skin disorders, was also assessed. All the measurements were performed by the same investigator.

The robot uses a pneumatic-driven artificial muscle developed at the Tokyo Institute of Technology. This artificial muscle consists of a mechanism that contracts with air sent from a compressor and has a diameter of 2–5 mm (thinner than previous artificial muscles) and the ability to be bundled or interwoven like actual muscle fibers.

The length of the artificial muscle for extension in this robot was adjustable, and was adjusted for each patient so that the distal interphalangeal (DIP) and proximal interphalangeal (PIP) joints had flexion of 0°, and the metacarpophalangeal (MP) joint had flexion of 30° when attached. The pneumatic pressure was set at 0.4 MPa for all patients.

This study was a “specified clinical trial” approved by the Institutional Review Board of Akita University and Ministry of Health, Labour and Welfare (approval number jRCTs022200012).

This study was performed after obtaining written informed consent from the patients.

### Results

The changes in the passive ROM of each joint before and after rehabilitation are shown in Table 1. All three patients showed partial improvements, but mild exacerbation (85° to 80°) was seen only in the MP joint of the index finger in patient 2. However, a change was seen from 75° of flexion and 10° of extension before rehabilitation to 80° of flexion and 0° of extension after rehabilitation, suggesting improvement in flexion.

MAS was improved in the index finger only in patients 1 and 3, while patient 2 showed improvements in all fingers. None of the fingers in any of the patients showed worsening spasticity (Table 2).

The finger circumference of all fingers except the thumb improved in case 1, and none of the fingers showed worsening (Table 3).

**Table 1.** Changes in the range of motion of each joint before and after training.

Case 1				Case 2				Case 3			
		Before training	After 3 weeks			Before training	After 3 weeks			Before training	After 3 weeks
		(°)	(°)			(°)	(°)			(°)	(°)
Thumb	IP	70	70	Thumb	IP	50	55	Thumb	IP	50	60
	MP	80	80	Thumb	MP	50	50	Thumb	MP	40	50
Index finger	DIP	40	50	Index finger	DIP	45	50	Index finger	DIP	35	50
	PIP	70	70	Index finger	PIP	80	90	Index finger	PIP	70	90
	MP	90	90	Index finger	MP	85	80	Index finger	MP	90	90
Middle finger	DIP	30	30	Middle finger	DIP	40	40	Middle finger	DIP	35	45
	PIP	90	90	Middle finger	PIP	75	80	Middle finger	PIP	60	70
	MP	80	80	Middle finger	MP	90	95	Middle finger	MP	90	90
Ring finger	DIP	40	40	Ring finger	DIP	35	35	Ring finger	DIP	50	60
	PIP	80	80	Ring finger	PIP	70	75	Ring finger	PIP	80	90
	MP	90	90	Ring finger	MP	90	100	Ring finger	MP	90	90
Little finger	DIP	50	50	Little finger	DIP	50	50	Little finger	DIP	50	60
	PIP	90	90	Little finger	PIP	70	75	Little finger	PIP	80	80
	MP	90	100	Little finger	MP	80	90	Little finger	MP	90	90

IP, interphalangeal; MP, metacarpophalangeal; DIP, distal interphalangeal; PIP, proximal interphalangeal.

**Table 2.** Change in Modified Ashworth Scale (MAS) of finger flexors before and after training.

Case 1			Case 2			Case 3					
		Before training	After 3 weeks			Before training	After 3 weeks			Before training	After 3 weeks
Thumb		1	1	Thumb		1	0	Thumb		1	1
Index finger		1+	1	Index finger		1+	1	Index finger		1+	1
Middle finger		1+	1+	Middle finger		1+	1	Middle finger		1	1
Ring finger		1+	1+	Ring finger		1+	1	Ring finger		1	1
Little finger		0	0	Little finger		1+	1	Little finger		1	1

**Table 3.** Change in finger circumference before and after training.

Case 1			Case 2			Case 3					
		Before training	After 3 weeks			Before training	After 3 weeks			Before training	After 3 weeks
		(mm)	(mm)			(mm)	(mm)			(mm)	(mm)
Thumb		73	73	Thumb		71	70	Thumb		70	65
Index finger		72	69	Index finger		74	70	Index finger		72	65
Middle finger		74	69	Middle finger		70	68	Middle finger		73	62
Ring finger		68	66	Ring finger		63	60	Ring finger		65	60
Little finger		58	56	Little finger		53	52	Little finger		55	50

No adverse events were identified in any of the cases.

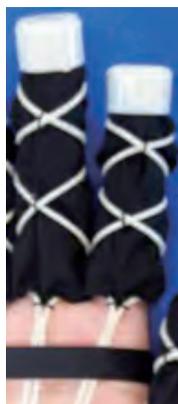
### Discussion

To the best of our knowledge, no previous reports have described rehabilitation using a wearable robot

with pneumatic artificial muscles, such as in this report, as a CPM device for finger spasticity. In this study, improvements in ROM and finger circumference were obtained through rehabilitation using a wearable robot with pneumatic artificial muscles as a CPM device for post-stroke finger spasticity. Improvements in spasticity were also identified.

Although various reports have described wearable robots for the fingers [6–14], their structures can be classified into two types: motor-driven and pneumatic. Reports on motor-driven robots include exoskeleton types and those using cables. Li et al. [8] and Diez et al. [9] reported the utility of systems that combine sensory feedback in exoskeleton-type wearable robots. Of those using cables, Araujo et al. [10] reported a wearable robot that can be controlled by brain waves. Yurkewich et al. [11] devised a wearable robot using cables that move based on forearm electromyograms, and reported that its use in nine stroke patients showed significant improvements in the Fugl-Meyer Assessment-Hand and the Chedoke Arm and Hand Activity Inventory. Yap et al. [12] reported that a grasping action was possible in pneumatically driven wearable robots using pneumatic artificial muscles. Chen et al. [13] developed a wearable robot using silicone tubes operated by air pressure and used it in a patient with Parkinson's disease having reduced hand function and reported that the robot could perform grasping movements as well. While structures such as these have been reported, Sun et al. [14] reported that pneumatically-driven wearable robots were superior to motor-driven types in terms of compliance, flexibility, and safety, and were therefore more useful in hand rehabilitation. This may be attributed to the use of pneumatic artificial muscles.

In this study, improvements in passive ROM and spasticity may be attributed to three structural features of the robot. The first is the three-point bending structure (Figure 2), in which intersections of the artificial muscles for flexion that are wrapped around the fingers are located on the DIP, PIP, and MP joints, respectively, allowing flexion force to act efficiently in finger flexion. The second is the flat braided design (Figure 3), which allows a sufficiently antagonizable strong torque against flexion contracture, which is a specific aftereffect of stroke, to act with the attachment



**Figure 2.** Three-point bending structure. The intersections of the artificial muscles for flexion that are wrapped around the fingers are located on the distal interphalangeal (DIP) joint, proximal interphalangeal (PIP) joint, and metacarpophalangeal joint.

of the seven interwoven artificial muscles for extension. The third is the elastic plate (Figure 4) attached to the DIP and PIP joints on the dorsal side of the hand, which effectively provides extension force by the principle of leverage because the ends of the plate are located at the DIP and PIP joints.

Moreover, the constant torque of this robot owing to air pressure may have also contributed to its effectiveness. Yeh et al. [4] compared rehabilitation using a CPM device that moved with a constant torque and a CPM device that moved with a constant angle in patients with spasticity of the legs. Although the results showed improvements in spasticity and ROM with both the constant torque type and the constant angle type, the constant torque CPM device was more effective. The wearable robot used in the present study was a constant torque type, which may have helped produce good results.



**Figure 3.** Flat-braided design. Seven interwoven artificial muscles for extension are attached to the back of the hand.



**Figure 4.** Elastic plate. This is attached to the DIP and PIP joints on the dorsal side of the hand.

In this study, the circumference of nearly all fingers improved, suggesting improvement in venous return. Bonnaire et al. [15] reported that when an ankle joint CPM device was used in healthy individuals, return in the femoral vein was found to be elevated, showing that venous return improved with passive flexion and extension of joints. In our robot, in addition to passive flexion and extension of each finger, the artificial muscles for flexion that are wrapped around each finger contract intermittently, thereby acting as a pump on the fingers. This may have improved venous return more effectively.

Finally, in a previous study using this wearable robot, Koizumi et al. [16] reported that a healthy individual under relaxed conditions was able to hold a 500 g water bottle with the attachment of the wearable robot. The use of this robot may thus be feasible not only in rehabilitation for spasticity that occurs in the chronic stage of stroke, but also in rehabilitation for paralysis that occurs in the acute stage of stroke, and as a support in daily life.

The limitation of this study is that the sample size was too small to make a statistical comparison. We plan to continue the study and increase the number of cases in the future.

### Conclusion

In conclusion, we developed a wearable robot for the fingers that uses pneumatic artificial muscles to improve finger ROM and MAS, and that appears potentially useful in rehabilitation for spasticity. With increase in finger circumference, venous return also seemed to be improved.

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