Development of Shoulder Exoskeleton toward BMI triggered Rehabilitation Robot Therapy

Tomoyuki Noda[1], *Member, IEEE*, Tatsuya Teramae[1], Jun-ichiro Furukawa[1], *Member, IEEE*
Miho Ogura[2], Kohei Okuyama[2], Michiyuki Kawakami[2], Meigen Liu[2] and Jun Morimoto[1], *Member, IEEE*

***Abstract*— Since exoskeletons show potential for rehabilitation therapy, many scientists have been designing upper extremity exoskeletons. Unfortunately, few have successfully provided a shoulder exoskeleton for severe impairment. Toward Brain-Machine-Interface (BMI) rehabilitation robot therapies for severe upper extremity impairment, this paper introduces a shoulder exoskeleton robot with a modular joint and an off-board modular actuator. We applied a Modular Exoskeletal Joint (MEJ) to a shoulder exoskeleton that was driven by Pneumatic Artificial Muscles (PAMs) transmitted by a Bowden cable. Our objective is generating passive movements triggered by BMI. Since large torque has to be generated for assist a whole arm, we newly designed a more powerful Nested-cylinder PAMs (NcPAMs) than our previous work. As a proof of the concept of the mechatronics design, we show the tracking performance of the periodic trajectory of a joint angle with both human and mannequin arms as simulated impairments. Our result shows that the tracking error is sufficiently small in all of the conditions and that our developed shoulder exoskeleton is an adequate substitute for flexion/extension movements.**

I. Introduction

Since the number of people who suffer from brain strokes and require rehabilitation therapy continues to increase[1], demand is also rising to address and recover from the limitations of motor functions. Recovering from upper extremity impairment is critical for daily activities. In the case of moderate impairment, increasing the use of paretic upper extremities with constraint-induced therapies [2] is an effective intervention. However, scant intervention has been specifically aimed for severe impairments [3][4]. One traditional rehabilitation role for severe impairment is learning how to use such residual functions as handedness exchanges.

The Brain Computer Interface (BCI), which is connected to robotic rehabilitation systems (for example, Brain Machine Interface (BMI) rehabilitation), is a promising approach to improve the motor performance of severe impairment. Shindo et al. [4] detected motor imagery by an electroencephalogram-based (EEG-based) BCI interface and triggered hand movements to induce the neuroplasticity of severe impairments. Applying a BCI interface to spinal cord injury patients has also been studied [5]Transcranial direct current stimulation (tDCS) has simultaneously been used with a forearm exoskeleton [6][7][8][9].

Since upper extremity exoskeletons also play an important role in rehabilitation called robot therapy [10]several upper extremity exoskeletons have been developed as robotic rehabilitation platforms. However, conventional BMI exoskeleton platforms are limited to the planar movement of arms or the flexion/extension of elbows or wrists/hands. To the best of our knowledge, no study has successfully applied a BMI exoskeleton to shoulder flexion/extension with severe impairment. This omission might reflect that creating torque, which fully substitutes for the motor function of flexion/extension movements, is challenging, such as the passive range-of-motion of a whole arms inertia and against gravity.

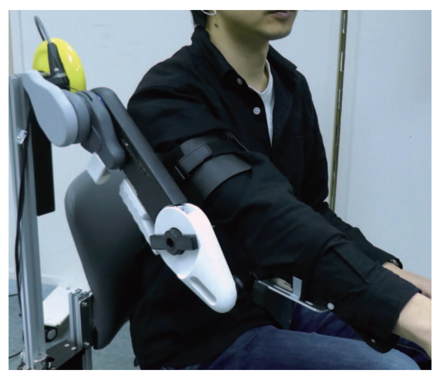

Fig. 1. Developed upper extremity exoskeleton for shoulder flexion/extension

Over the last decade, multi-degree freedom exoskeleton platforms using electric motors have been developed. For example, Reogo [11] has an endpoint of 3 degrees of freedom (DoF). However, due to endpoint guiding systems, elevating the shoulder may increase the risk of impingement or subluxation in severe impairment. Recon et al. [12](WOTAS) developed a 4-DoF exoskeleton for forearm movements (elbow F/E and wrist F/E with pronation-supination of the forearm), and ETS-MARSE [13]and ARMin II [14]are 7-DoF whole arm exoskeletons. These exoskeleton platforms implement electric motors directly to active joints. However, since increasing the gear ratio causes loose back-drivability, the gear ratio must be kept low. Thus, many platforms add a passive balancing counterweight or a spring to lower the torque

[1]The authors are with ATR Computational Neuroscience Laboratories, 2-2-2 Hikaridai, Seika-cho, Soraku-gun, Kyoto 619-0288, Japan t_noda@atr.jp, [2]The authors are with Keio University School of Medicine, Tokyo, Japan. Nao Nakano and Akihide Inano helped with the hardware maintenance in the experimental setup. This research was supported in part by the following: Development of Medical Devices and Systems for Advanced Medical Services from AMED and Development of BMI Technologies for Clinical Applications, carried out under SRPBS by the MEXT/AMED, AMED under Grant Number JP17dm0107034 and JP18he0402255, National Institute of Information and Communications Technology (NICT), ImPACT Program of the Council for Science, Technology and Innovation (Cabinet Office, Government of Japan), a project commissioned by NEDO. T. N. was partially supported by JSPS KAKENHI 15H05321.

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Fig. 2. 3D Cad model of upper extremity exoskeleton

demand of electric motors in the shoulder. Consequently, a multi-DoF platform might increase the entire exoskeleton's size, mass, and inertia. Wu et al. [15] and Perry et al. [16] remotely implemented a servo motor using Bowden cables and a tendon transmission system to reduce the exoskeleton arms weight. However, the transmission structures become too large and complex, complicating and impeding wide acceptance in rehabilitation institutions.

Moreover, to guarantee safety, implementing compliance at the hardware level is critical, especially as the joint torque increases. Exoskeletons with hydraulic actuators implement an elastic element between actuators and joints [17][18]. Stienen et al. [19] developed a hydro-elastic actuator that contains a compact torsional spring. However, hydraulic fluid cannot store energy or distribute/transmit primary pressure. A high-powered energy source is required, e.g., a large compressor. If oil is used as a hydraulic, careful seal maintenance is required to avoid leaks to protect the environment. The hydraulics may be appropriate for industrial applications of exoskeletons.

A pneumatic actuator stores energy as pressurized fluid and is inherently compliant without installing any elastic element. Pneumatic actuators may also provide an advantage in a BMI interface by lowering noise more than electric motors. Previously, we developed a shoulder exoskeleton using a pneumatic piston as an actuator [20]In this paper, we incorporate Pneumatic Artificial Muscles (PAMs) [21] with a Bowden cable force transmission system in a shoulder torque source. A PAM is lightweight and provides large peak torque benefits. Huang et al. [22] developed upper extremity exoskeletons, in which each joint is driven directly by PAMs that are allocated as well as the links. For composing a compact exoskeleton arm, Bowden cable transmission systems combined with off-board PAMs were previously proposed [23] [24]

However, after conventional PAMs with a Bowden cable transmission system were introduced to the environment, the PAM bladder may be damaged. Conventional studies have failed to scrutinize the risk of pneumatic explosions.

Moreover, after installing an exoskeleton into a clinical scene, the design may need to be improved to properly fit a variety of clinical demands and kinds of patients. Conventional designs suffer from many modification limitations since the actuator and joint designs are intricately interrelated.

Based on the above background, one promising approach is to modularize the joint and actuator designs. Thus, we apply Nested-cylinder Pneumatic Artificial Muscle (NcPAM) and Modular Exoskeletal Joints (MEJ), which were developed in our previous work that robotized ankle-foot orthosis [25]. In this paper, we developed a larger NcPAM to generate and transmit adequate torque to fully substitute for the shoulder flexion/extension movement.

The remainder of this paper is organized as follows. Section II describes state-of-the-art mechatronics designs. Section III describes and discusses our experimental setup and results to prove its design concept using the developed shoulder exoskeleton (Fig. 1). We finally conclude in Section IV.

II. Mechatronics Design

Figures 2 and 3 illustrate an overview of state-of-the-art mechatronics design. Joints, actuators, and links are the core components of an exoskeleton robot. In this paper, we applied NcPAM and MEJ, both of which were developed for robotizing ankle-foot-orthosis (AFO) [25], to an upper extremity exoskeleton. We used the basic design of the link adjustment structure and the control unit [20], which includes height and link length adjustments.

In this paper, we focus on the development and the improvement of the mechanical design of the actuator (NcPAM) and the joint (MEJ) that can be applied to the upper extremities. To generate adequate torque for a shoulder exoskeleton, we newly developed a more powerful NcPAM than our previous work[25]. Table I summarizes the specifications of an upper-extremity exoskelton and details the state-of-the-art mechanical design below:

TABLE I

Summary of upper-extremity exoskeleton

Spec. list (upper extremity exoskeleton)	
Spec.	Value
Weight (arm total)	5 kg
Encoder	Optical 3 phase 4000 CPR
Maximum pressure	0.8MPa
Nominal maximum torque	48 Nm

A Pneumatic Artificial Muscle (PAM), combined with a tendon, requires a tensioner to properly maintain the tendons route[21].We addressed this problem by developing a NcPAM [25] in which the state-of-the-art structure includes a cable tensioner inside the PAM bladder. In Fig. 3, NcPAMs antagonistically transmit contraction force by Bowden cables (brake cables from Shimano Co. Ltd.). The right side of NcPAM (NcPAM1) is for the flexion torque, and its left side (NcPAM2) is for the extension torque. Due to the

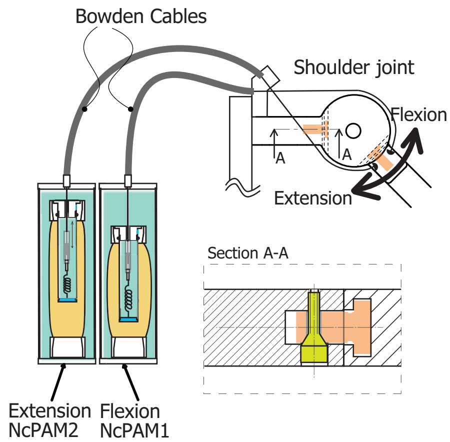

Fig. 3. Mechanical design of NcPAMs and MEJ

tensioner embedded in the nested cylinder, each NcPAM can be compactly enclosed in an external cylinder to improve the modular design. The external cylinders bottom edge is connected to one edge of NcPAM, and the other side holds the outer housing of the Bowden cable. The outside cylinder is a mechanical shield to reduce the risk of physical damage or pneumatic explosions.

In Fig. 3, the Bowden cables are connected to the NcPAMs and the shoulder joint and are driven toward the flexion as NcPAM1 contracts. Although NcPAM2 is insufficiently inflated to transmit its force to the cable, the tensioner (a small spring in the nested cylinder embedded in NcPAM2) maintains a small cable tension. If neither of the NcPAMs is inflated, the shoulder joint becomes passive, because the spring force is enough small. We designed all the NcPAM parts except for the PAM rubber, whose material was cut from a commercially available PAM (FESTO Co. Ltd., MAS-20).

The core structure of a shoulder joint is composed of an MEJ whose stator and rotor sides have a T-slot and a 15-mm x 25-mm aluminum frame (Yukigiken Co. Ltd., F152) that can be connected to a T-lock with a tapered screw (Sections A–A in Fig. 3). The aluminum frames stator side is connected to a block that holds the other side of the outer housing of the Bowden cables. Inner cables are connected to the aluminum frame (rotor side) and manipulate the pulley to generate shoulder torque. In this setup, MEJ has a cantilever axis, and a large force from the NcPAM has to be loaded. Since the maximum nominal force of each NcPAM was 1500 N, MEJ is mechanically reinforced. Note that all the screws can be tightened/loosened from the sagittal plane for simple maintenance.

The MEJ pullys diameter was 64 mm. Within this compact body, there were two radial bearings and a 3-phase reflective encoder (4000 CPR). Since the encoder is embedded inside the thrust bearing, no mechanical coupling is required.

III. Experiments

A. Experimental setup

The control unit manages the pressure regulator (VP50 Norgren Co., Ltd.) and has multi-functional interfaces: digital to analog (DA), analog to digital (AD), a quadrature encoder interface (QEI), and IO ports. All the interfaces were controlled in a real-time system (Xenomai with RTNet) on Python script. The control frequency was set to 250 Hz. The NcPAMs were connected to the pressure regulator by a 8-mm polyurethane air tube whose inner diameter was 5 mm. Dried air as primary pressure was remotely and silently supplied from a scroll type air compressor.

B. Control method

To validate the shoulder exoskeletons design (Fig. 1), we tracked the performance of the periodic movements. As a control method, we used a previous learning scheme [25]. The feed-forward pressure, which is expressed by locally weighted regression, is iteratively updated based on the error using Iterative Learning Control (ILC) [26]. In the experiment, we used only NcPAM1; NcPAM2 was not inflated:

$$\Delta P_1^{(i+1)}(\phi) \leftarrow \Delta P_1^{(i)}(\phi) + Ke(\phi+\lambda), \tag{1}$$

where ϕ denotes the movement phase, P_1 denotes the feedforward NcPAM1 pressure to be learned, K denotes the update gain, $e(\phi)$ denotes the tracking error, and λ is the expected delay of the pneumatic system. We set the update gain to 10% of the error ($K = 0.1$ MPa/rad) and the pneumatic delay to 80 msec ($\lambda = 0.08$ sec). The parameters of the locally weighted regression were initialized to zero, and the feed-forward pressure trajectory was learned using 20 iterative trials. One iteration was 8 seconds, and 2 cycles of data (4 seconds) were extracted in the middle of the experiment.

C. Experimental results

Our experiments goal was to trigger the periodic flexion/extension as passive movement of a shoulder joint. To do so, we attached a mannequin arm to the developed exoskeleton to simulate a paralyzed arm (Fig. 4).

Figures 5(a)–(c) show the tracking performance of a 0.5-Hz sinusoidal movement of 40 ± 20 deg (equal to 0.70 ± 0.35 rad) for the desired movement without any load (Fig. 5(a)), with a human arm Fig. 5(b) like in Fig. 1), and with a mannequin arm Fig. 5(c)). As seen in Figs. 5(a)–(c), different pressure trajectories within a maximum pressure of 0.8 MPa were learned to track the desired trajectory, and smooth angle trajectories were generated.

Figures 6 show the tracking performance of the second order harmonic sinusoidal movement with the mannequin arm. In this experiment, we used the simulated trigger movements that tracked the performance of the sinusoidal movements (0.5 Hz 40 ± 20 deg plus 1 Hz ± 5 deg) for the desired movement. The NcPAM1 was gradually infrared at the initial pressure at $\phi = 0$, and the controller waited for the simulated BMI trigger. In Figs. 6, the time of zero is set to the timing of the trigger. In this experiment, since

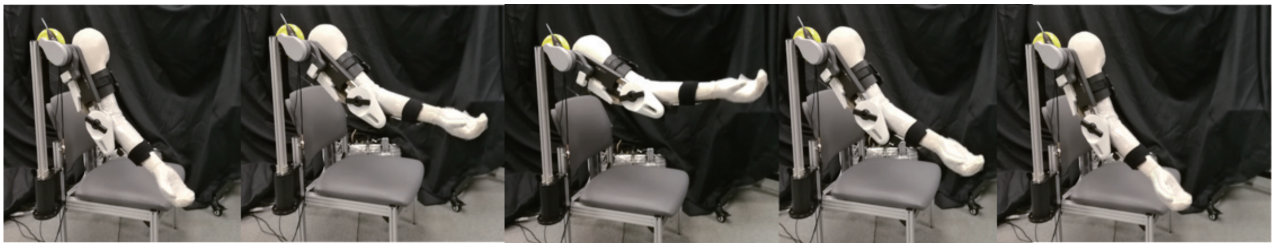

Fig. 4. Experimental setup: pictures of movement with mannequin arm.

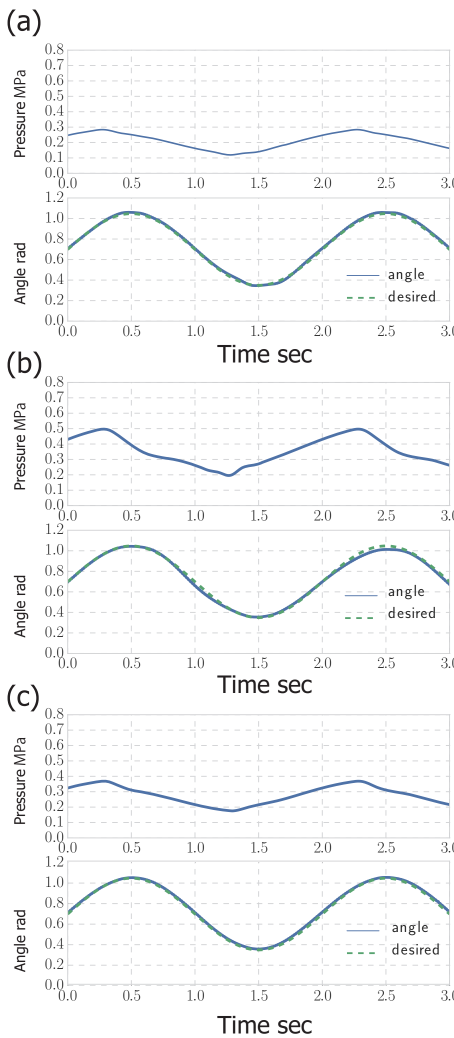

Fig. 5. Periodic tracking performance (0.5-Hz sinusoidal movement): (a) without an arm, (b) with a human arm, (c) with a mannequin arm.

the learned trajectory is for periodic movements, there is a difference between the initial position and the initial desired angle. After the movement was triggered, 0.5–1.0 seconds were necessary until we started to track the desired trajectory. After 1.5 seconds, the trajectory overall tracked the desired trajectory because the shoulder exoskeleton joint does not have gears and has mechanically low impedance. Increased impedance is required to reduce the error of the early tracking performance. Using an antagonist NcPAM (NcPAM2) is needed to increase the impedance to reduce the initial error. When patients use this platform, their shoulders may have different dynamics that are altered in time. The risk of a type of spastic paralysis has to be considered.

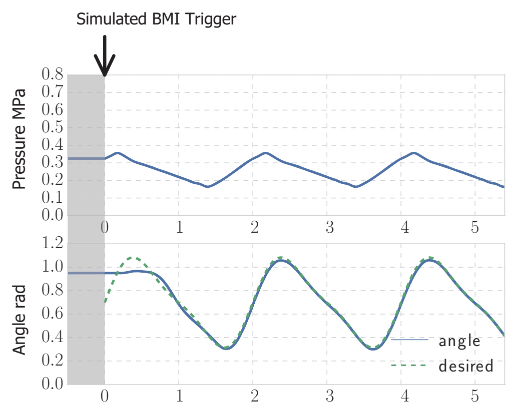

Fig. 6. Triggered periodic movement of second order harmonic (1 Hz + 0.5 Hz) sinusoidal

IV. CONCLUSIONS

We developed a shoulder exoskeleton with a modular design in a joint and actuator system toward Brain-Machine-Interface (BMI) rehabilitation for the severe shoulder impairment of brain stroke patients. This paper first explained that many conventional upper-extremity exoskeleton platforms are focused on forearm movement or transverse planes. Incorporating the movement of a shoulder flexion/extension tends to make systems too large and complex due to counterweights or springs that lower the torque demand. This is because shoulder flexion/extension is challenging because of the difficulty of generating adequate torque against the gravity and inertia of a whole arm, and the joint has to be back-drivable and inherently compliant.

We adopted a Modular Exoskeletal Joint (MEJ) and Nested-cylinder Pneumatic Artificial Muscles (NcPAMs) into shoulder flexion/extension and developed NcPAMs with a 20-mm diameter PAM bladder. In our experiment, the periodic pressure pattern is learned to track the sinusoidal desired angle trajectory. We iteratively updated the parameters of the locally weighted regression using Iterative Learning Control (ILC). We did tracking performance experiments with three conditions: without load, with a healthy human arm, and with a mannequin arm as a simulated impairment. Periodic 0.5-Hz sinusoidal movements were used for the desired trajectory, which was successfully tracked in all the conditions. However, when the movement was triggered, error was observed until the trajectory began to crack just after the movement was triggered. To deal with such challenges, future work must improve the controller. We are currently conducting a study with patients who are using this shoulder exoskeleton platform in a rehabilitation clinic.

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