ELECTROMYOGRAPHY (EMG)-DRIVEN NEUROMUSCULAR ELECTRICAL STIMULATION (NMES) AND ROBOT HYBRID SYSTEM FOR UPPER LIMB REHABILITATION AFTER STROKE

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PhD

The Hong Kong Polytechnic University

2021

The Hong Kong Polytechnic University

Department of Biomedical Engineering

Electromyography (EMG)-Driven Neuromuscular Electrical Stimulation (NMES) and Robot Hybrid System for Upper Limb Rehabilitation after Stroke

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A thesis submitted in partial fulfilment of the

requirements for the degree of Doctor of Philosophy

August 2020

CERTIFICATE OF ORIGINALITY

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ABSTRACT

Upper limb motor deficits are noted in more than 80% of stroke survivors. Restoration of limb function requires repeated-and-intensive practice of the paralyzed limb with maximized voluntary motor effort and minimized compensatory motions in close-to-normal muscular coordination. While electromyography (EMG)-driven neuromuscular electrical stimulation (NMES) robot assisted therapy has been suggested for repeated-and-intensive upper limb training with maximized voluntary motor effort, and minimized the compensatory motions, it remains challenging. The main difficulties are as follows: (1) EMG-driven NMES-robot assisted therapy for hand function recovery was under investigation although impaired hand dexterity is a major disability of the upper limb after stroke; (2) long-term rehabilitation methods with potential for self-help training by stroke survivors are urgently required to improve the independency of stroke survivors and decrease the burden on the healthcare system because of the expanding stroke population and insufficiency of professional staff worldwide. However, suitable technologies for these methods are currently lacking; and (3) most outpatients with chronic stroke experienced upper limb impairments, especially in the distal joints. However, they have limited access to the treatment in public healthcare system because of resource constraints. The objectives of this study were: (1) investigation of the rehabilitation effectiveness of an EMG-driven NMES-robotic hand assisted upper limb training, (2) development of a novel EMG-driven NMES-robot (i.e., exoneuromusculoskeleton) for self-help upper limb rehabilitation, and (3) investigation of the feasibility and rehabilitation effectiveness of home-based self-help training

assisted by an EMG-driven wrist/hand exoneuromusculoskeleton. This study was divided into the following three parts:

In the first part, a clinical trial with single-group design was conducted on participants with chronic stroke (n = 15) who received 20 sessions of EMG-driven NMES-robotic hand assisted upper limb training. The results suggested that device-assisted upper limb training was effective for improving voluntary motor functions and muscle coordination in the paretic upper limb. Furthermore, these improvements were maintained after 3 months.

In the second part, a novel EMG-driven exoneuromusculoskeleton was developed. The system integrated the NMES, soft pneumatic muscle, and exoskeleton techniques, for self-help upper limb training after stroke. The developed system could assist the elbow, wrist, and fingers to perform sequential limb task under voluntary effort control through EMG, with a lightweight, compact, and low power-requirement design. The pressure-torque transmission properties of the designed musculoskeletons were quantified, and the assistive capability of the system was evaluated on patients with chronic stroke (n = 10). The feasibility of the developed system for self-help operation and rehabilitation effects were also investigated in a pilot single-group trial (n = 15). The results suggested that the developed system could effectively support self-help upper limb rehabilitation after stroke.

In the third part, the feasibility of using the EMG-driven wrist/hand exoneuromusculoskeleton for home-based self-help upper limb training, and its rehabilitation effects were investigated on participants with chronic stroke (n = 11) in a

clinical trial with single-group design. The EMG-driven wrist/hand exoneuromusculoskeleton could assist self-help upper limb training in a home setting, and was effective in improving motor functions of the paretic upper limb.

In conclusion, repeated-and-intensive upper limb training with coordinated hand movements assisted by the EMG-driven NMES-robotic hand could facilitate hand function recovery and improve muscular coordination in the paretic limb. A novel EMG-driven exoneuromusculoskeleton was developed for self-help upper limb rehabilitation, which could assist the physical practice of the paretic upper limb. The system could assist self-help upper limb training in both laboratory and home settings, and was effective for improving voluntary motor control, muscular coordination, and reducing muscle spasticity of the paretic upper limb.

PUBLICATIONS ARISING FROM THE THESIS

Journal Publications

(1) **C.Y. Nam**, W. Rong, W.M. Li, Y. Xie, X.L. Hu, Y.P. Zheng. The effects of upper limb training assisted with an electromyography-driven neuromuscular electrical stimulation robotic hand on chronic stroke. Frontiers in neurology, 2017, 8, 679. DOI: 10.3389/fneur.2017.00679

(2) Q.Y. Qian, **C.Y. Nam**, Z.Q. Guo, Y.H. Huang, X.L. Hu, S.C. Ng, Y.P. Zheng, W.S. Poon. Distal versus proximal - an investigation on different supportive strategies by robots for upper limb rehabilitation after stroke: a randomized controlled trial. Journal of NeuroEngineering and Rehabilitation, 2019, 16(1):64-64.

(3) Y.H. Huang[1], **C.Y. Nam[1]**, W.M. Li, W. Rong, Y.N. Xie, Y.C. Liu, Q.Y. Qian, X.L. Hu. A comparison of the rehabilitation effectiveness of neuromuscular electrical stimulation robotic hand training and pure robotic hand training after stroke: a randomized controlled trial. Biomedical Signal Processing and Control, 2020, 56, 101723. [1]Contributed equally to this work.

(4) **C.Y. Nam**, W. Rong, W.M. Li, C.Y. Cheung, W.K. Ngai, T.C. Cheung, M.K. Pang, L. Li, J.Y. Hu, H.W. Wai, X.L. Hu. An exoneuromusculoskeleton for self-help upper limb rehabilitation after stroke. Soft Robotics, 2020. DOI: 10.1089/soro.2020.0090.

(5) F.Q. Ye, B.B. Yang, **C.Y. Nam**, Y. Xie, F. Chen, X.L. Hu. A data-driven investigation on surface electromyogram based clinical assessment in chronic stroke. Frontiers in Neurorobotics. 2021. Under revision.

(6) **C.Y. Nam**, B.B. Zhang, T.Y. Chow, F.Q. Ye, Y.H. Huang, Z.Q. GUO, W.M. Li, W. Rong, X.L. Hu, W.S. Poon. Home-based self-help telerehabilitation of the upper limb assisted by an electromyography-driven wrist/hand exoneuromusculoskeleton after stroke. Journal of NeuroEngineering and Rehabilitation, 2021. Submitted.

Conference publications and presentations

(1) **C.Y. NAM**, X.L. HU, Y.N. XIE, W.M. LI, W. RONG. Post-stroke upper limb rehabilitation assisted with electromyography (EMG)-driven functional electrical stimulation (FES) – robotic hand, IEEE EMBS Hong Kong-Macau Joint Chapter Student Competition 2016.

(2) **C.Y. NAM**, X.L. HU, Z.Q. GUO, K.M. CHAN, Y.N. XIE, K.L. WONG, W. RONG, W. M. LI, Y.P. ZHENG. Leap motion-based upper limb rehabilitation and evaluation system, Engineering Medical Innovation Global Competition 2016.

(3) **C.Y. NAM**, X.L. HU, Z.Q. GUO, K.M. CHAN, Y.N. XIE, K.L. WONG, W. RONG, W. M. LI, Y.P. ZHENG. Leap motion-based upper limb training and evaluation system for post-stroke rehabilitation, 8th WACBE World Congress on Bioengineering 2017.

(4) Z.Q. GUO, X.L. HU, **C.Y. NAM**, Y.P. ZHENG. Evaluation of assistive capability of a neuromuscular electrical stimulation-robotic hybrid rehabilitation device, 8th WACBE World Congress on Bioengineering 2017.

(5) X.L. Hu., W. RONG, W.M. LI, **C.Y. NAM**, H. W. WAI, J. NGAI, E. CHEUNG, L. LI. J.Y. HU, Pang, L. Li, W. S. Poon. Mobile exoneuromusculoskeleton for self-help post-stroke upper limb rehabilitation. 47th International Exhibition of Inventions of

Geneva 2019. Gold Medal; Prize of the Polish Patents Office, Poland; Special Merit Award from the Ministry of Education, Thailand.

(6) **C.Y. NAM**, W. Rong, W.M. Li, X.L. Hu. Mobile exoneuromusculoskeleton for upper limb rehabilitation after stroke. IEEE EMBS Hong Kong-Macau Joint Chapter Student Competition 2019. First Prize in postgraduate Group.

(7) Hu, X.L., W. Rong, W.M. Li, **C.Y. Nam**, Y.J. Wei, T.C. Cheung, H.H. Wai, J.Y. Hu. Mobile exoneuromusculoskeleton for upper limb rehabilitation after stroke, The 9th WACBE World Congress on Bioengineering (WACBE 2019).

(8) F.Q. Ye, **C.Y. Nam**, W.M. Li, W. Rong, F. Chen, X.L. Hu. A data-driven investigation on surface electromyogram based clinical assessment in chronic stroke. IEEE EMBS Hong Kong-Macau Joint Chapter Student Competition 2020.

Patent

(1) Hu, X.L., W. Rong, W.M. Li, **C.Y. Nam**, Y.J. Wei, T.C. Cheung, H.H. Wai, J.Y. Hu. Physical rehabilitation apparatus, method, computer storage medium and electronic device. 2018. China. Applicant: The Hong Kong Polytechnic University. Publication number: WO 2019/134594. Application number: PCT/CN2018/125005. Filed on 2 Jan, 2018. Published on 9 Jul, 2019.

Book chapter

(1) Q.Y. Qian, **C.Y. Nam**, Rong, W.M. Li, Z.Q. Guo, Y.H. Huang, X.L. Hu, S.C. Ng, Y.P. Zheng, W.S. Poon. Robotic and Neuromuscular Electrical Stimulation (NMES) Hybrid System. In: Intelligent Biomechatronics in Neurorehabilitation, 2019. Edited by Xiaoling Hu. ELSEVIER Academic Press, ISBN 9780128149430. 2019:147-166.

ACKNOWLEDGEMENTS

My deepest gratitude goes to my chief supervisor, Dr. Xiaoling Hu, for her supervision, patient guidance and tremendous support in my research. I have received valuable experiences and knowledge under her inspiration and guidance of my PhD study.

I would like to sincerely thank my co-supervisor, Prof. Yong-ping Zheng, for his trust and support in this research and warm encouragement throughout the study.

I heartful thank all collaborators in this research, Mr. Wei Rong, Mr. Waiming Li, Miss Tszching Cheung, Mr. Wingkit Ngai, Mr. Mankit Pang, Dr. Honwah Wai, Dr. Li Li, and Dr. Junyan Hu, for their technical supports and advice on the development of the robotic system.

I would like to extend my thanks to my colleagues, Dr. Yanhuan Huang, Dr. Qiuyang Qian, Mr. Ziqi Guo and Mr. Fuqiang Ye, for their assists in human subject experiments. Many thanks go to the other members of the team for their time and efforts in this study.

I would like to express my gratefulness to all participants in this research, for their time and effort.

I am fortunate and honoured to have my family, who supported me with unconditional love, faith, and encouragement.

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LIST OF ABBREVIATIONS

ADLs	Activities of Daily Living
APB	Abductor Pollicis Brevis
ARAT	Action Research Arm Test
BIC	Biceps Brachii
CI	Co-contraction Index
ECU	Extensor Carpi Ulnaris
ED	Extensor Digitorum
EMG	Electromyography
ENMS	Exoneuromusculoskeleton
FCR	Flexor Carpi Radialis
FD	Flexor Digitorum
FIM	Functional Independence Measurement
FMA	Fugl-Meyer Assessment
FMA-SE	Fugl-Meyer Assessment for Shoulder/Elbow
FMA-WH	Fugl-Meyer Assessment for Wrist/Hand
MAS	Modified Ashworth Scale
MMSE	Mini Mental State Exam
MTD	Maximal Trunk Displacement
MVC	Maximum Voluntary Contraction
NMES	Neuromuscular Electrical Stimulation
NMU	Number of Movement Unit
RCT	Randomized Controlled Trial
ROM	Range of Motion
TRI	Triceps Brachii
UE	Upper Extremity
VR	Virtual Reality
WH-ENMS	Wrist/Hand Exoneuromusculoskeleton
WMFT	Wolf Motor Function Test

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CHAPTER 1

INTRODUCTION

1.1 Upper limb rehabilitation after stroke

1.1.1 Background

Stroke is a leading cause of adult disability in both developed and developing countries.[1, 2] Since the beginning of the 20th century, stroke mortality has been remarkably declined.[3, 4] As stated in the Hong Kong Hospital Authority Statistical Reports 2005-2013, the number of annual stroke admissions to the public hospitals has been increasing from 11,062 cases in 1981 to 24,555 in 2012; however, the mortality has been declining from 29.4% to 13.3% over the same period.[5] Accumulated stroke survivors were approximately 300,000 in Hong Kong, with around 25,000 annual stroke cases to the public hospitals.[6] In mainland China, accumulated stroke survivors were more than 8 million in 2016, with an average new case occurrence of 2 million per year and an increase of 8% annually from 2009 to 2016 in Mainland China.[7] In 2016, there were approximately 80 million prevalent cases of stroke globally.[8] The large amount of stroke populations lead to large demands of rehabilitation treatments and low productivity, and require social security allowance (e.g., normal / higher disability allowance) and caregiver. The above factors significantly contributed to the social costs and economic burden directly and indirectly.

Approximately 80% of stroke survivors have upper limb impairments, which greatly affects the independency of their daily living.[9, 10] Patients with stroke require long-term rehabilitation for reducing upper limb impairment.[11] In contrast to the expending stroke populations, resources (e.g., healthcare professionals, the length of hospital stay of a patient) in the rehabilitation industry are lacking even in developed centuries.[12] In Hong Kong, regular rehabilitation services in public hospitals usually could be accessed in the first year after stroke, i.e., an average of 3-4 weeks' hospital stay followed with an outpatient service of one to two visits per week.[6] There is a large amount of accumulated stroke survivors with little regular support from the public healthcare system for rehabilitation after the first year of stroke. Therefore, effective and self-help rehabilitation methods[13, 14] are need for long-term upper limb rehabilitation demanded by the large stroke populations for improving their independency and to decrease the burden on the healthcare system.

1.1.2 Poststroke upper limb motor impairment

Upper limb motor deficits are noted in more than 80% of stroke survivors,[9, 10] affecting the independence and the social appearance of the stroke survivors in their daily life. Only 18% of stroke survivors with severe paralysis achieve complete upper limb function recovery within the subacute period.[15] Only 50% of stroke survivors likely to regain some functional use of their upper limb with the traditional physical therapies and the upper limb recovery is poorer in comparison with that of the lower limb, since the movement patterns of the upper limb are more diverse and delicate than the lower limb, associated with the neuromuscular coordination of multi-joint of the upper limb for performing daily tasks, including feeding, grooming and dressing.[16] In the current

upper limb rehabilitation after stroke, significant motor improvements are mainly achieved in the proximal joints, and approximately 65% of patients with chronic stroke cannot incorporate their affected hand into their usual activities,[17] markedly affecting their independence and ability to perform activities of daily living (ADLs). This is related to the spontaneous motor return with a sequence from the proximal to distal joints in the early stage after stroke, and the difficulty in traditional physical therapy by human therapists to manage the coordinated movements among the upper limb joints at the same time, especially at the small and distal joints (e.g., wrist and fingers), resulting in most of the patients experienced reasonable motor recovery of their proximal joints (i.e., shoulder and the elbow) but limited recovery at the distal joints.[18, 19]

1.1.3 Neurorehabilitation after stroke

Neurorehabilitation after stroke is a process of motor relearning on the lost limb functions.[20, 21] The traditional viewpoint on rehabilitation after stroke suggested that significant motor restoration mainly occurs in the first six months after the onset of a stroke, i.e., acute and subacute periods.[22] Nevertheless, more recent studies have shown that significant motor improvements in the chronic period after stroke (i.e., after the first six months) also could be achieved by physical training as intensive as for the subacute inpatients.[23, 24] However, regular and intensive physical training usually is hard to be obtained by discharged patients, according to the current management in the medical care system with a shortage of professional manpower.

Restoration of post-stroke limb function depends on repeated-and-intensive practice of

the paralysed limb[21, 25, 26] with maximized voluntary motor effort[27, 28] and minimized compensatory motions,[28, 29] leading to enhancement of the recruited alternative neuromuscular pathways with close-to-normal muscular coordination. The success of motor recovery after stroke firstly depends on the maximized involvement of voluntary intention and participation from patient's own paretic neuromuscular systems during physical limb practice.[27, 28] Intensive and repetitive physical practice with voluntary efforts could facilitate a process of neural network reorganization (i.e., neuroplasticity) in the unimpaired area of the central nervous system. It is similar to the motor learning of all skillful tasks associated with a procedure of improving the motor skills, the smoothness and accuracy of movements. Both human and animal studies suggested that repeated voluntary physical experience after stroke is a major modulator for the neuroplasticity process in the nervous system associated with functional recovery.[27, 30] Secondly, it also depends on a close-to-normal limb coordination practice during the training, which may reduce the unnecessary compensatory motions in the paretic limbs.[28, 29]

1.2 Rehabilitation of the upper limb assisted with devices

1.2.1 Neuromuscular Electrical Stimulation (NMES)

NMES is a neural prosthetic technique to mimic the stimulation from nerve to muscle, and has been applied to patients with stroke for rehabilitation purpose.[31-33] A paretic muscle can be activated to contract by NMES often applied transcutaneously.[34] A

mechanism of the therapeutic effects of NMES is that a cyclic electrical stimulation on muscles would produce repetitive sensorimotor experiences. These experiences not only improve the paretic muscle force, but also would either trigger one or all of the following pathways associated with neuroplasticity – functional reorganization, where intact areas assume function of damaged area, or activation of alternate descending pathways and structures in injured side.[19] NMES has been found to be effective for improving the muscle force and enhancing sensory feedbacks for motor relearning after stroke.[35] It also improved learned disuse and limb neglect after stroke and reduced compensatory muscle activities during physical limb practice due to afferent sensory input to the nervous system evoked by the precise electrical stimulation on the paretic muscles.[36] However, using NMES alone is difficult in controlling motion kinematics, such as range of motion (ROM) and trajectory due to limited stimulating precision in fine motor control.[37]

1.2.2 Rehabilitation Robots

Post-stroke physical therapy is a labor demanding and arduous process for both the therapist and the patient due to the intensive and repetitive physical practice. Therefore, various rehabilitation robots/exoskeletons with mechanical motors have been developed as assistance to the therapist, providing intensive physical training with high repetition.[38] In comparison with NMES systems, rehabilitation robots are usually large in size and much heavier, and should be operated under direct supervision of professionals. However, the mechanical support to the disabled limbs by robots are more effective than that by NMES, since it is relative easier to control the kinematic parameters, e.g., ROM and trajectory, by external motors in a robot during limb

movements, which is necessary for motor relearning after stroke.[28] However, using robot alone cannot directly activate the desired muscle groups as NMES during the training, the external force exerted from a robot cannot efficiently correct the compensatory muscle activations during physical limb practice.

Most upper limb rehabilitation robots are designed for proximal joints and not required incorporating the whole upper limb or hand movements during rehabilitation. For example, the MIT-MANUS, a commercially available robot for shoulder and elbow practice, and used to provide repetitive training with planar reaching movements. Significant motor gains in shoulder and elbow were observed after the training, but no positive rehabilitation outcomes in wrist and hand were observed after the training,[39] as revealed by the measurement of the Fugl-Meyer Assessment.[40] The Bi-Manus-Track assisted is a wrist trainer.[41] In the Bi-Manus-Track assisted training, the forearm and wrist movements had been emphasized, with limited proximal joint and hand practice, leading to no functional outcomes of the whole upper limb and limited motor improvements of the proximal joints.[42, 43] Robot assisted training included coordinated motions at the distal joints with the proximal of the paretic limb are needed for effective upper limb rehabilitation.

In addition, the involvement of voluntary effort has not been integrated in most of NMES and robotic devices. Continuous passive motion (CPM; i.e., no voluntary effort required from a user) is a common control strategy adopted.[38] It has been reported that CPM mainly could release the muscle spasticity after stroke, but contributed little to the long-term voluntary motor improvement.[38] The bio-signals frequently used for indication of voluntary intention in the voluntary-triggered systems are

electromyography (EMG, the electrical signal generated in muscles under the control of the nervous system)[44], and limb kinematic parameters, such as limb torques, trajectory and acceleration.[45] EMG-driven strategy is expanding techniques and has been used to indicate voluntary intentions in robot assisted rehabilitation,[46] and to maximize voluntary motor effort during practice for better improvements in voluntary motor functions with longer sustainability compared with those with passive limb motions.[47] Rehabilitation devices for reducing compensatory muscle activities and maximize the voluntary involvement during the training are required for effective rehabilitation after stroke.

1.2.3 EMG-driven NMES and Robot Hybrid Systems for the Upper Limb

NMES can selectively activate target muscles for a desired muscular coordinating pattern. However, it is hard for NMES alone to achieve accurate kinematic qualities. In contrary to NMES, robot can provide external mechanical support to a joint with desired kinematics controlled by actuators. However, robotic assistance could not directly correct muscular discoordination in a paretic limb. Therefore, by taking the advantages of both NMES and robotic techniques, NMES has been combined with mechanical robots in physical training after stroke.[48] NMES could improve proprioception in target muscles, reducing compensation from alternative muscle synergies;[36] meanwhile the robotic assistance could provide sensorimotor experiences with precise kinematics in desired movements.[39] The combined NMES-robot has been found to be more effective than either NMES or robot solo treatments in post-stroke

upper-limb rehabilitation, particularly in improving the muscular coordination by reducing muscular compensation.[34]

In addition, a series of voluntary intention driven NMES-robotic systems have been developed[49-54], with the purpose to support repeated-and-intensive practice of the paretic limb with maximized voluntary motor effort and minimized compensatory motions, for effective upper limb rehabilitation after stroke. An EMG-driven NMES-robot for wrist rehabilitation was developed previously.[49, 51] In this system, both NMES and robot compartments will give assistance at the same time to the paretic wrist joint of a stroke survivor when performing wrist extension/flexion tasks. A randomised clinical trial was conducted to evaluate the training effectiveness of this EMG-driven NMES-robot system, in comparison with the purely EMG-driven robot (i.e., without the augmentation of NMES).[51] The results showed that the combined NMES-robot treatment achieved more significant motor improvements and better muscle coordination in the forearm muscles, and the motor gains could persist for 3 months after the training.[51] It is also found that the motor recovery process was faster with the NMES-robot combined training than the pure robot treatment.[51] An EMG-driven NMES-robotic hand system was designed for rehabilitation on the distal fingers.[52] When the robotic fingers help a paretic hand performing hand close/open tasks, NMES will be delivered to the finger flexor and extensor to evoke the respective muscle contractions. However, seldom has work been done in the investigation of the combined effects of EMG-driven NMES-robotic hand for upper limb rehabilitation. In addition, the rehabilitation effects of EMG-driven NMES-robotic hand assisted upper limb training had not been investigated. An NMES-robotic exoskeleton for multi-joint coordinated rehabilitation on the whole upper limb was designed (i.e., the

Rehabilitation Sleeve).[54] The system can facilitate a person after stroke to practice the coordinated limb tasks, including arm reaching, hand open/close and arm withdrawing. Multi-channel NMES, together with the assistances from the motors at the elbow and wrist joints, help a user complete the multi-joint coordinated tasks for the whole upper limb.[54] The power required from the motor system of the robot part could be less than a pure robot, since NMES can evoke additional muscular power directly from the biological neuromuscular system. Thus, reduced the size and weight of the motors for the mechanical part in the NMES-robot system. The weight of the Rehabilitation Sleeve mounted on the upper limb (950 g) was lighter than the contemporary exoskeletons providing the similar multi-joint functions. However, professional operation in clinical environment was still required while using the system. This is related to the prevention of misalignments of the rigid materials and the electrical motors during repeated practice, due to nonnegligible weights mounted onto the paretic limb; and high power consumption for the actuations need of the system in generating enough torque to support not only paralyzed limbs, but also the weight of the system worn onto the body.

1.3 Self-help upper limb rehabilitation

Self-help and effective rehabilitation with minimum professional assistance are in urgent need for large stroke populations.[55] However, the related technology is lacking.[13, 14] Mobile exoskeletons are an emerging technology with wearable application.[14] These exoskeletons are powered by portable batteries and have potential for user-independent self-help rehabilitation that can be accessed anytime, even in unconventional environments (e.g., at home).[14, 56, 57] However, most available upper limb exoskeletons

for wearable and portable rehabilitation purposes are rigid, heavy and high power consumptions,[13, 56-58] triggering electrical safety concerns for user-independent usage, leading to requirement of close assistance of professionals for use in conventional environments (e.g., hospitals and clinics). In addition, the rigid exoskeleton composed of rigid materials and actuated by electrical motors, are constrained by their heavy weight and low torque-to-weight ratio, which limit their user-independent applications. In contrary to the heavy and rigid exoskeleton, pneumatic robots (pneumatic muscles) are light-in-weight of the wearable part as actuated by air, have been commonly adopted actuation for the upper limb, especially for distal joints.[59, 60] However, pneumatic systems are usually bulky and slow in power transmission from pressure to torque during air inflation by compressors for needed air volume and pressure compared with electrical motor actuation in rigid exoskeleton to achieve equivalent mechanical outputs (e.g., joint torque).[60, 61] Large and high-power compressors connected to the pneumatic muscles constrain these devices for user-independent applications.[59] Artificial muscle has not been integrated with the NMES and exoskeleton techniques yet currently. It has been known that NMES can reduced the mechanical scale and power-requirement of the entire system due to the evoked muscular effort. Therefore, a novel lightweight mechanical design is required to achieve optimized body-device integration with fast power transmission, high torque-to-weight ratios, and low power consumption for user-independent self-help rehabilitation, which could be achieved by integrating the NMES, soft pneumatic muscle, and exoskeleton techniques in one system. In addition, a new rehabilitation program of self-help upper limb training for patients with stroke is also needed.

1.4 Objectives of the Study

Long-term upper limb rehabilitation is challenging because of insufficiency of professional manpower. Effective and self-help rehabilitation with minimum professional assistance is in urgent need. Restoration of limb function depends on repeated-and-intensive practice of the paretic limb with maximized voluntary motor effort and minimized compensatory motions, which could be achieved using the EMG-driven NMES-robot hybrid systems. However, the main obstacles in current rehabilitation techniques for successful self-help upper limb rehabilitation after stroke are: (1) impaired hand dexterity is a major disability of the upper limb after stroke, and loss of hand function and finger dexterity causing a great impact on ADLs of the stroke survivors. However, previous studies on combinations of NMES and robotic systems have mainly focused on motor recovery of the elbow and wrist joints, few works have been done in EMG-driven NMES-robot assisted therapy for hand function recovery, and the effects of the EMG-driven NMES-robotic assisted training was under investigation; (2) long-term rehabilitation methods with potential for self-help training by stroke survivors are urgently required because of the expanding stroke population and insufficiency of professional staff worldwide. However, suitable technologies for these methods are currently lacking; and (3) most outpatients with chronic stroke experienced upper limb impairments, especially in the distal joints (i.e., wrist and fingers). However, they have limited access to the treatment in public healthcare system because of resource constraints.

Therefore, the objectives of this study include:

(1) To investigate and confirm the rehabilitation effects of an EMG-driven NMES-

robotic hand assisted upper limb training.

(2) To develop of a novel EMG-driven NMES-robot for self-help upper limb rehabilitation, to evaluate the assistive capability of the developed system, and to investigate the feasibility of using the developed system in self-help training and the rehabilitation effects of the system.

(3) To investigation of the feasibility and rehabilitation effects of home-based self-help training using the developed EMG-driven NMES-robot to assist the distal joints.

CHAPTER 2

THE EFFECTS OF UPPER-LIMB TRAINING ASSISTED WITH AN ELECTROMYOGRAPHY (EMG)-DRIVEN NEUROMUSCULAR ELECTRICAL STIMULATION (NMES) ROBOTIC HAND ON CHRONIC STROKE

2.1 Introduction

Stroke is a major cause of adult disability, and patients with stroke require regular and long-term medical care for reducing physical impairments.[11] Under a fifth of stroke survivors with severe paralysis achieve complete upper limb function recovery in the first six months after the onset (i.e., the subacute period).[15] Moreover, about two-thirds of patients with chronic stroke (i.e., 6 months after the onset of a stroke) cannot incorporate their paretic hand into their usual activities,[17] Thus, their independence and ability to perform activities of daily living (ADLs) is highly impacted.

The traditional perspective on neurorehabilitation after stroke, significant motor recovery usually occurs during the subacute period and associated with a spontaneous recovery in the early period, and motor improvements are expected to be minimal or plateaued during the chronic period.[30] Nevertheless, more recent studies on post-stroke rehabilitation have shown that repetitive and high-intensity practice facilitate motor recovery[25, 62] and intensive therapeutic interventions can contribute to significant improvements in motor functions of the upper limb in chronic period after stroke.[24] However, compared to the large amount of stroke populations, resource (e.g., healthcare professionals) in the rehabilitation industry are lacking, leading to a difficulty in provision of repeated intensive rehabilitation training through traditional "one-to-one" manual-physical therapy.[63] Rehabilitation robots have been proposed to fill this gap through assisting the repetitive therapeutic tasks intensively under supervision by a therapist.[64] Various robotic systems have been developed and suggested for hand rehabilitation after stroke (e.g., Haptic Master[65, 66] and HapticKnob[42]) and their training effects had been investigated. These studies have indicated that hand function recovery could be achieved by robot-assisted therapy because the robotic system can provide intensive physical training with repeated motions to persons after stroke through a consistent and precise manner over a long period of time. Moreover, the integration of voluntary effort into robotic design has been recommended for post-stroke rehabilitation.[47] Training designs with this "add-on" feature of voluntary effort from the residual neuromuscular pathways exhibited superior motor improvements and longer sustainability than did passive limb motion training. Electromyography (EMG)-driven strategy is a rapidly expanding technique, which has been used to indicate the voluntary intentions from the residual muscles after stroke. In the past decade, many EMG-driven controls for rehabilitation robots have been designed,[46] and a set of EMG-driven robot-

assisted training systems have also been developed for upper limb rehabilitation after stroke in our previous works. [47, 67, 68] Those EMG-driven training systems have exhibited significant motor outcomes in the paretic upper limb for chronic stroke patients, especially in voluntary motor controls.[46, 69]

Despite the adoption of the EMG-driven strategy has been widely adopted, the use of robot-assisted therapy still remains suboptimal. For instance, using robot alone cannot directly activate the desired muscle groups during the training, the external force exerted from a robot cannot efficiently correct the compensatory muscle activations during physical limb practice.[70] In contrast to robot systems, neuromuscular electrical stimulation (NMES) can generate repetitive muscular contractions to produce functionally useful movements, by applying electrical stimulation to target muscles, evoke sensory feedback to the brain during muscle contraction, and promote motor relearning.[71] However, difficulties would be encountered while activating groups of muscles for dynamic movements of the upper limb through the use of NMES alone. Using NMES alone is difficult in controlling motion kinematics, such as range of motion (ROM) and trajectory due to limited stimulating precision in fine motor control.[37] Consequently, a combination of NMES and robot assisted therapy has been developed for upper limb rehabilitation,[51, 72-74] and those studies have shown that this combination is effective for motor function recovery in patients with chronic stroke A randomised clinical trial was conducted to evaluate the training effectiveness of this EMG-driven NMES-robot system, in comparison with the purely EMG-driven robot (i.e., without the augmentation of NMES).[51] The results showed that the combined NMES-robot treatment achieved more significant motor improvements and better muscle coordination in the forearm muscles, and the motor gains could persist for 3

months after the training.[51] It is also found that the motor recovery process was faster with the NMES-robot combined training than the pure robot treatment.[51]

However, previous studies on combinations of NMES and robotic systems have mainly focused on motor recovery of the elbow and wrist joints.[51, 72-74] Thus far, only a few studies have reported EMG-driven NMES robot-assisted therapy for hand function recovery although loss of hand function is the primary factor of the upper limb disability after stroke.[39] In our previous work, an EMG-driven NMES exoskeletal hand robot, which could provide fine control of the hand movements and activating the target muscles selectively for fingers extension/flexion, was developed and suggested for hand rehabilitation after stroke,[52] where the assistive capacity of the NMES and robot combined system in helping persons with chronic stroke conducting finger extension flexion were compared with either NMES or robot assistive schemes. NMES and robot combined scheme showed higher motion accuracy and superior muscle coordination in the whole upper limb. However, the rehabilitation efficacy and the training effects had not been well investigated by clinical trials previously. In this work, the rehabilitation effectiveness of the EMG-driven NMES robotic hand assisted upper limb training on chronic stroke was investigated by a single-group trial. We hypothesized that the participants who received intensive and repetitive upper limb training with coordinated hand movements assisted by the EMG-driven NMES robotic hand would demonstrate improvements in hand function and muscular coordination of the fingers.

2.2 Methods

2.2.1 EMG-driven NMES Robotic Hand

The EMG-driven NMES robotic hand system used in this study is shown in Figure 2-1A. The system can provide assistance for finger extension and flexion of the paretic limb of patients with stroke.

The wearable robotic hand (Firgelli L12, Firgelli Technologies Inc.) provided individual mechanical assistance to the five fingers, and each finger was actuated by a linear actuator (Figure 2-1B).[52, 75] The proximal and distal section of the index, middle, ring and little fingers were rotated around the virtual centers located at the metacarpophalangeal (MCP) and proximal interphalangeal (PIP). The thumb was rotated around the virtual center of its MCP joint. The finger assembly provided two degrees of freedom (DOF) for each finger and offered a range of motion (ROM) of 55˚ and 65˚ for the MCP and PIP joints, respectively. The angular rotation speeds of the two joints were set as 22˚/s and 26˚/s at the MCP and PIP joints, respectively, during training.

The NMES electrode pair (30mm diameter; Axelgaard Corp., Fallbroo, CA) provided stimulation during finger extension, was attached over the extensor digitorum (ED) muscle. The configuration for the EMG and NMES electrodes on the ED muscle is shown in Figure 2-1C. The outputs of NMES were square pulses with a constant amplitude of 70 V, stimulation frequency of 40 Hz, and a manually adjustable pulse

width in the range 0-300 μs. Before the training, the pulse width was set at the minimum intensity, which achieved a fully extended position of the fingers in each patient. No assistance from NMES was provided during finger flexion to avoid the possible increase of finger spasticity after stimulation.

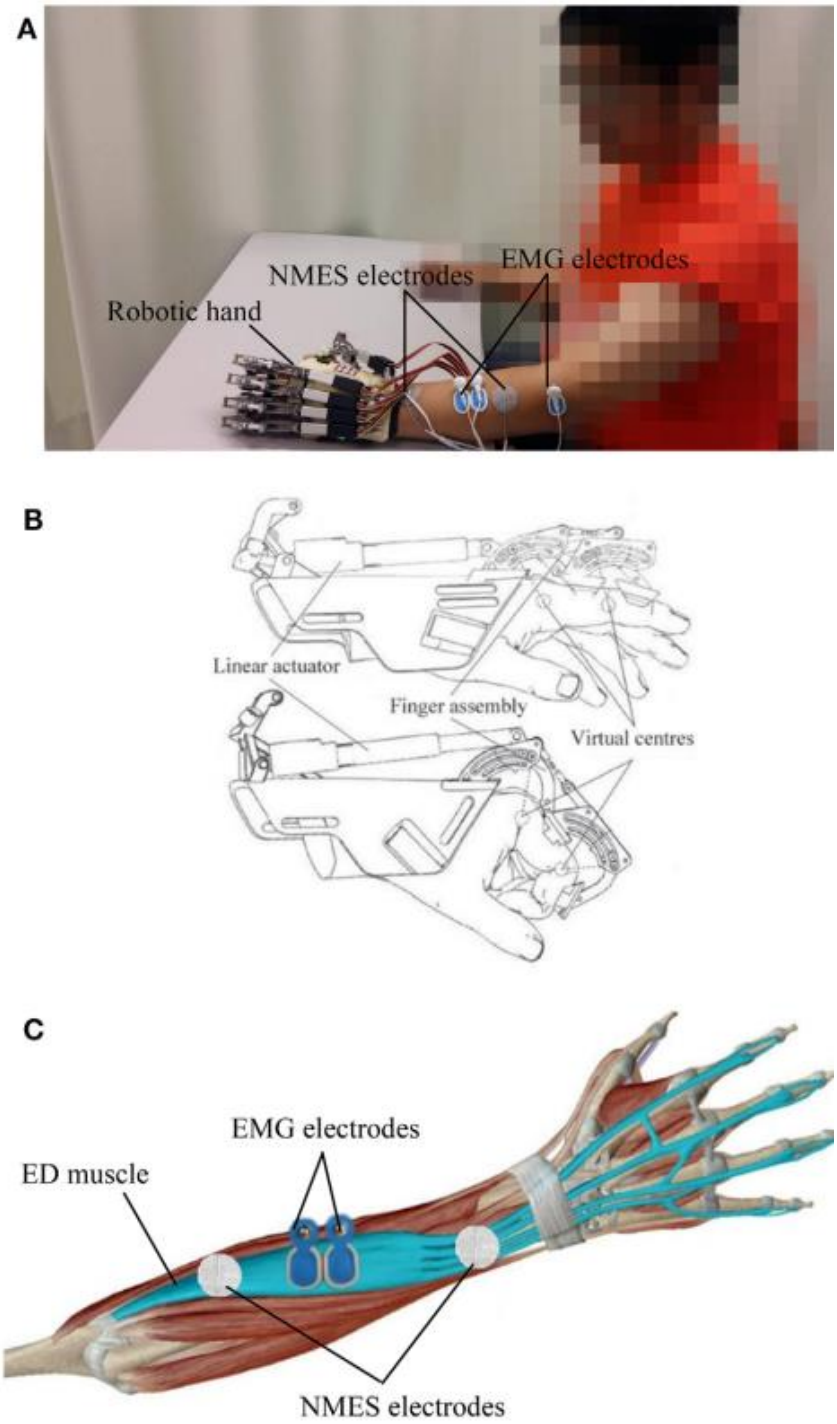

Figure 2-1. The EMG-driven NMES robotic hand system: (A) the wearable system

consisting of a mechanical exoskeleton of the robotic hand, a pair of NMES electrodes attached to the ED muscle and EMG electrodes on the ED and APB muscles; (B) illustration of the mechanical structure of the robotic hand; (C) the EMG and NMES electrodes configuration on the ED muscle.

The abductor pollicis brevis (APB) and ED muscles were used as voluntary neuromuscular drives to control robot assistance and NMES assistance from the system to facilitate performance of phasic and sequential limb tasks, namely, hand closing and hand opening. The APB was selected as the driving muscle in the hand closing phase, since the EMG signals from the APB of the paretic limb after stroke are less affected by spasticity and are relatively easier to be controlled than the FD muscle for finger movements in chronic stroke.[76] EMG-triggered control was adopted in this work. Three times of the standard deviation (SD) above the EMG baseline in the resting state was set as a threshold level in each motion phase during training. In the "hand closing" phase, as soon as the EMG activation level of the APB muscle reached a preset threshold (3 SD above the baseline), the robotic hand would close with a constant speed (22˚/s and 26˚/s at the MCP and PIP joints, respectively) and provide mechanical assistance for finger flexion motions. In the "hand opening" phase, once the EMG activation level of the ED muscle reached a preset threshold (3 SD above the baseline), the robotic hand would open with a constant speed (22˚/s and 26˚/s at the MCP and PIP joints, respectively) and NMES would stimulate the ED muscle during the entire hand opening phase to assist finger extension motions. Once the assistance of the system was initiated, voluntary effort from the patient was not required and the assistance from the NMES and robotic parts would be continuously provided during the entire hand closing and opening phase in the defined ROM.

The EMG signals from the driving muscles captured using EMG electrodes (Blue Sensor N, Ambu Inc. with a contact area of 20 × 30 mm) were first amplified 1000 times (preamplifier: INA 333; Texas Instruments Inc., Dallas, TX), sampled at 1000 Hz by using a data acquisition card (DAQ, 6218 NI DAQ card; National Instruments Corp) and filtered by using a band-pass filter in the range 10-500 Hz. After digitization, the EMG signals from the APB and ED muscles were rectified and low-pass filtered (fourth-order, zero-phase forward and reverse Butterworth filter; cut-off frequency, 10 Hz) to obtain an envelope of EMG signals (i.e., the EMG activation level) in the real-time control.

2.2.2 Participants

After obtaining ethical approval from the Human Subjects Ethics Sub-committee of the Hong Kong Polytechnic University, participants in this study were recruited from the local districts through advertisement. A total of 20 patients were screened for the training during the subject recruitment. Fifteen participants with chronic post-stroke hemiparesis met the inclusion criteria and were recruited in this study after obtaining their written consents. Inclusion criteria were as follows: (1) at least 1 year after the onset of a singular and unilateral brain lesion due to stroke; (2) the spasticity at the elbow, the wrist and the fingers were ≤3 as measured by the Modified Ashworth Scale (MAS);[77] (3) motor impairments in the affected upper limb range from severe to moderate according to the Fugl-Meyer Assessment (FMA; 15 < FMA < 45, with a maximal score of 66 for the upper limb);[40] (4) presence of no visual deficit and the

ability to understand and follow simple instructions, as assessed by the Mini-Mental State Examination (MMSE > 21);[78] (5) presence of detectable voluntary EMG signals from the driving muscle on the affected side (three times the SD above the EMG baseline); (6) both the MCP and PIP joints could be extended to 180° passively. Subjects were excluded because of the following conditions: (1) did not fulfill the above inclusion criteria, (2) currently pregnant, (3) had an implanted pacemaker.

2.2.3 Training protocol

All participants received the EMG-driven NMES robotic hand assisted upper limb training, which consisted of 20 training sessions with the intensity of 3-5 sessions/week, within 7 consecutive weeks.

2.2.3.1 Session-by-session pre-training evaluation task

An evaluation was conducted at the beginning of each training session. Each participant was first subjected to a maximum voluntary contraction (MVC) test for the following five target muscles: APB, ED, flexor digitorum (FD), biceps brachii (BIC) and triceps brachii (TRI). EMG electrode pairs with center separation of 2 cm were attached to the skin surface of the muscles of interest according to the configuration specified in Cram's work.[79] Then, each participant was instructed to perform a bare hand evaluation task, which was used to monitor the muscle coordination during the recovery, as we did previously in EMG-driven hand robot-assisted upper limb training of patients with chronic stroke.[75] During evaluation, participants were seated at a table to maintain a vertical distance of 30–40 cm between the table surface and the participants' shoulder.

While conducting the MVC test on the ED and FD muscles, participants were seated at a table and the paretic upper limb was placed on the table with elbow joint extended at an angle of 130˚, the wrist was held by an experimental operator and positioned around its neutral position, and the finger positions were set by the operator to obtain an angle around 150˚ at the MCP joints of the index, middle, ring and little fingers. During the maximum extension of the four fingers, the ED EMG signals were recorded; and during the maximum flexion, the FD EMG signals were captured. For the MVC test on the APB, the operator held the thumb in an extended position (around 30º) and asked the participants to conduct maximum thumb palmar abduction with the same configuration of the wrist and elbow joints as in the ED and FD MVC tests. During the MVC test on the BIC and TRI muscles, the paretic upper limb was positioned with the shoulder abducted at 70˚ and the elbow flexed at 90˚. The MVC test on each target muscle was repeated twice and the contraction was maintained for 5 s. The variation of maximum EMG amplitude in the two repetitions was required to be within 10%, otherwise the MVC test would be repeated. The maximum EMG amplitude was selected as the EMG amplitude of MVC for the target muscle. A 2-min rest was provided between two consecutives contractions to avoid muscle fatigue.

After the MVC test, the bare hand evaluation task was performed, which involved lateral and vertical arm reaching-grasping tasks.[75] The participants were required to use their paretic limbs to perform the task (without assistance from NMES or the robotic hand) and complete it at their natural speed. In the lateral task, each participant was instructed to grasp a sponge (thickness 5 cm, weight 30 g) that was placed on one side of a table near the paretic side of the participant, transport the sponge 50 cm horizontally, release it, grasp it again, then return it to the starting point, and release it. In the vertical

task, each participant was instructed to grasp the sponge on the mid-line of the lower layer of a shelf, lift it through a vertical distance of 17 cm, place it on the mid-line of the upper layer of the shelf, grasp it again, then place it back on the starting point, and release it. Both lateral and vertical tasks were repeated thrice, with a 2-min break between two consecutive trials to prevent muscle fatigue.

The EMG recording was started when the participant began to grasp the sponge (as soon as one finger touched the sponge) to when the participant released the sponge at the starting point (all the fingers left the sponge). The EMG signals from the target muscles were first amplified 1000 times, filtered by a band-pass filter in the range 10-500 Hz, and full-wave rectified. The EMG signals were sampled at 1000 Hz by the data acquisition card and stored in the computer for off-line processing as we did previously.[67, 68] In the early sessions of the training, only two participants could release the sponge without using their unaffected hands. A 10-s maximum time limit was set at the end of the attempt of release action for participants who could not release the sponge within 10-s by using their paretic hands. If their paretic hands could not release the sponge within 10-s, the participants could use their unaffected hands to remove the sponge. The EMG signals beyond 10-s were excluded for analysis. At the 20th session of training, five participants could release the sponge without using their unaffected hands.

2.2.3.2 Training task assisted with the EMG-driven NMES robotic hand

Participants were required to perform lateral and vertical arm reaching–grasping tasks with the EMG-driven NMES robotic hand on the paretic side with same seating arrangement and movements as the previous evaluation. In each training session, the participants performed 30-min lateral and vertical tasks, respectively, with a 10-min interval between the tasks to prevent muscle fatigue. However, most of the participants (n = 12) could not sustain the weight of the paretic limb and the robotic hand without assistance. This was mainly due to weakness of the shoulder and elbow joints. Therefore, during the arm transportation, these participants were allowed to use their unaffected limb to provide self-aware minimal support at the wrist joint of the paretic limb. During the last training session, 10 participants could lift the affected limb while wearing the robotic hand.

2.2.4 Evaluation of training effects

2.2.4.1 Clinical Assessments

In this study, the clinical assessments were used for functional evaluation of each participant and are described as follows: the FMA that the full score is 66 for the upper limb assessment and has been sub-scaled into shoulder/elbow (42/66) and wrist/hand (24/66),[80] used for post-stroke measurement of motor functional impairment in

voluntary limb movements; the Action Research Arm Test (ARAT),[81] adopted to evaluate the upper limb functions with hand tasks included holding/releasing objects with different shapes, sizes and weights; the Wolf Motor Function Test (WMFT),[82] applied to collect the information on the motion speed and functional ability related to different daily tasks; the Motor Functional Independence Measure (FIM),[83] used for evaluation of subject's ADLs; and the MAS,[77] adopted to measure the spasticity of the flexors related to the elbow, wrist, and fingers. Before the training, the aforementioned clinical assessments were measured thrice in 2 weeks every 2-3 days to obtain the stability of baseline. The same clinical assessments were also measured immediately after the last training session and 3 months after the training by a training-blinded assessor who was instructed not to communicate regarding the training details with the participants and was not informed about the research purpose and the training protocol of this study.

2.2.4.2 Electromyography Parameters

For the cross-sessional monitoring, two EMG parameters were calculated which were (1) the normalized EMG activation level of each target muscle and (2) the normalized EMG Co-contraction Index (CI) between a muscle pairs.[67, 68] The EMG activation level of a muscle was calculated as follows:

$$\overline{\mathrm{EMG}} = \frac{1}{T}\int_0^T EMG_i(t)dt \qquad (Eq.1)$$

where $\overline{\mathrm{EMG}}$ referred to the averaged EMG envelope value of muscle i. The $EMG_i(t)$ was the EMG envelope signal after the normalization with respect to the EMG MVC

value of the muscle, and T was the length of the signal. Figure 2-2 shows the representative EMG signals and their normalized envelopes captured during a trial of lateral reaching-grasping task. To minimize the variations in the EMG levels of individual participant, the obtained EMG activation level in a session for an individual participant was further normalized using the following equation (Eq. 2), which consider the maximal and minimal EMG activation levels of a participant recorded across the 20 training sessions. The tendency of the EMG activation level (values varying from 0 to 1) of a participant across the 20 training sessions were obtained after this operation.

$$EMG_N = \frac{\overline{\mathrm{EMG}} - \overline{\mathrm{EMG}}_{min}}{\overline{\mathrm{EMG}}_{\max} - \overline{\mathrm{EMG}}_{min}} \qquad (Eq. 2)$$

where EMG_N was the normalized EMG activation level of muscle i. The $\overline{\mathrm{EMG}}$ referred to the averaged EMG envelope value of muscle i. The $\overline{\mathrm{EMG}}_{min}$ was the minimum value of the averaged EMG envelope across the 20 training sessions and the $\overline{\mathrm{EMG}}_{max}$ was the maximum value of the averaged EMG envelope across the 20 training sessions.

The CI between a pair of muscle was introduced and applied in our previous study,[67, 68] and expressed as follows:

$$\mathrm{CI} = \frac{1}{T}\int_0^T A_{ij}(t)dt \qquad (Eq. 3)$$

where $A_{ij}(t)$ was overlapping activity of EMG linear envelopes for muscles i and j, and T was the length of the signal. An increase in CI value represents an increased co-contraction phase of a muscle pair (broadened overlapping area), and a decrease in CI value indicates a decreased co-contraction phase of a muscle pair (lessened overlapping

area). The CI value was also further normalized, similar to the EMG activation level, for obtaining the tendency of muscle coordination, which considers the maximal and minimal CI values of a participant recorded across the 20 training sessions and its equation (Eq. 4) was given as follows:

$$CI_N = \frac{CI - CI_{min}}{CI_{max} - CI_{min}} \qquad (Eq. 4)$$

where CI_N was the normalized CI value between a pair of muscle i and j. CI_{min} was the minimum value of the averaged overlapping activity of EMG linear envelopes and CI_{max} was the maximum value of the averaged overlapping activity of EMG linear envelopes across the 20 training sessions. Session-by-session recording of the varying patterns of the two EMG parameters provided information particularly relevant to muscle activation and muscle coordination. Furthermore, it provided quantitative descriptions of the progress of motor function recovery of the paretic limb.

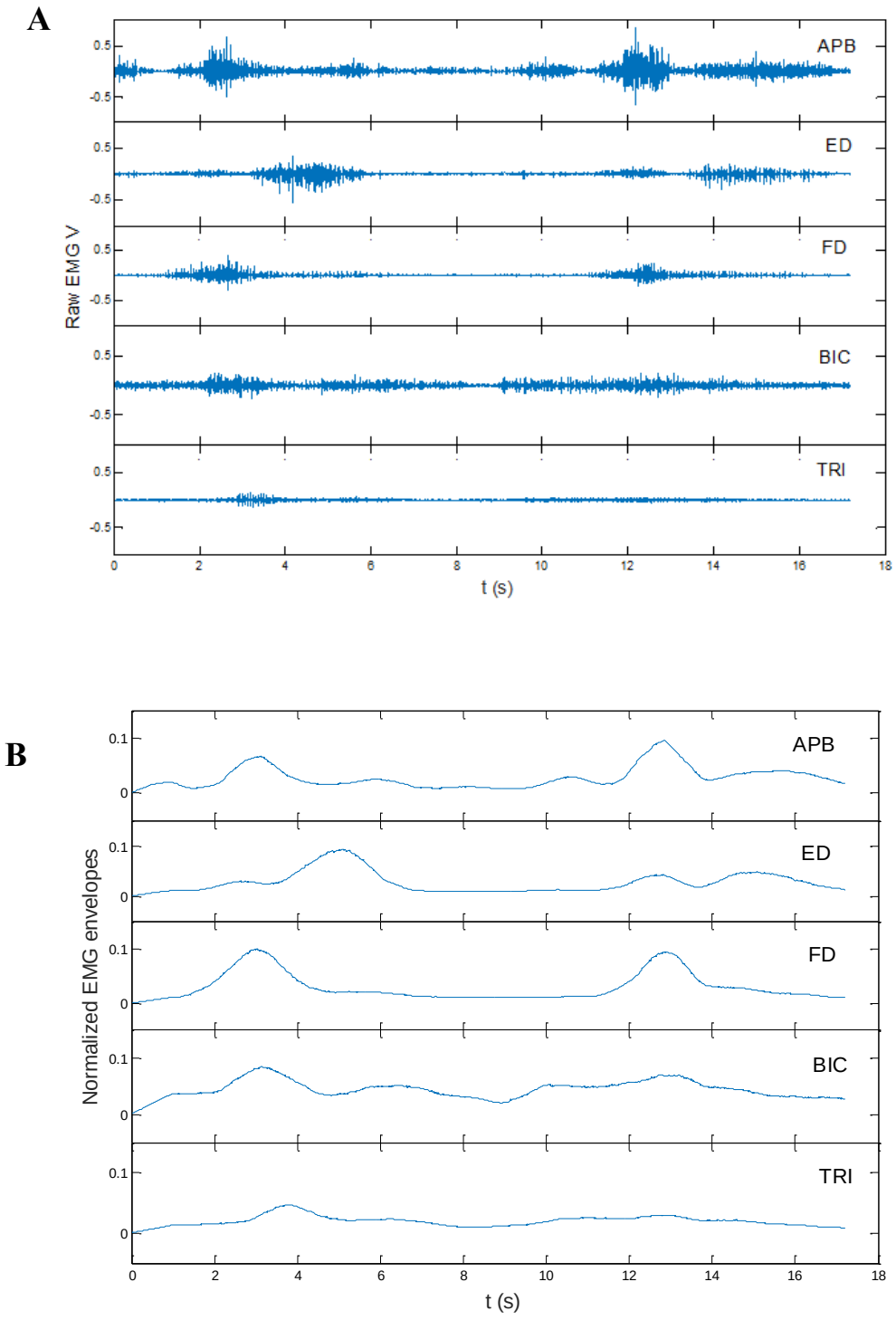

Figure 2-2. (A) The representative raw EMG trials in a lateral arm reaching-grasping task and (B) the EMG envelopes after rectification and normalization.

2.2.5 Statistics

The normality tests on the clinical scores and the EMG data by Lilliefors method were performed with a significant level of 0.05.[84] It found that the clinical score and the EMG sample had normal distribution ($p < 0.05$). One-way analysis of variance (ANOVA) with repeated measures (Bonferroni Post hoc test) were used to evaluate the differences on the clinical assessments across different time points (thrice pre-training assessments, a post-training assessment and a 3-month follow-up assessment) and the EMG parameters (i.e., the normalized EMG activation levels and the CIs) across the 20 training sessions. The levels of statistical significance were indicated at 0.05, 0.01 and 0.001 in this study.

2.3 Results

All recruited participants (n = 15) completed the EMG-driven NMES robotic hand assisted upper limb training. The demographic data of the participants are shown in Table 2-1. Table 2-2 lists all clinical scores measured in this study (i.e., the means and 95% confidence intervals of each clinical assessment together with the 1-way ANOVA probabilities with the effect sizes (EFs) for the evaluation with respect to the assessment sessions). Significantly difference clinical scores ($P< 0.05$, one-way ANOVA with Bonferroni post hoc test) are illustrated in Figure 2-3, which shows the FMA, ARAT and MAS scores evaluated at five time points: thrice pre-training assessments (Pre1, Pre2, Pre3), post-training assessments (Post), and 3-month follow-up assessment (3-month FU). Figure 2-3A to 2-3C show the variation in FMA scores at thrice pre-training assessments, post-training assessment, and 3 months follow-up assessment. In Figure 2-3A, the FMA full score significantly increased after the training, and this increase

was kept for 3-month ($P < 0.001$, EF = 0.313, $F = 7.96$, one-way ANOVA with Bonferroni post hoc test). In Figure 2-3B, a significant increase of the FMA wrist/hand score was detected after the training, and the increments maintained 3 months later ($P < 0.001$, EF = 0.228, $F = 5.18$, one-way ANOVA with Bonferroni post hoc test). A significant increase in the FMA shoulder/elbow score was observed after the training, and the increase maintained at the assessment at the 3-month follow-up (Figure 2-3C; $P < 0.001$, EF = 0.320, $F = 8.23$, one-way ANOVA with Bonferroni post hoc test). The variation in ARAT score at five time points is shown in Figure 2-3D. A significant increase in the ARAT score after the training was observed and this increase compared with the pre-training values was maintained for 3 months ($P < 0.01$, EF = 0.226, $F = 5.12$, one-way ANOVA with Bonferroni post hoc test). Figure 2-3E shows the variation in MAS scores at the finger, wrist, and elbow at five time points. A significant decrease in the MAS scores was observed in the assessments at different time points. The MAS scores at the elbow significantly declined after training, and these decreases maintained for 3 months ($P < 0.01$, EF = 0.214, $F = 4.77$, one-way ANOVA with Bonferroni post hoc test). Significant decreases were observed in the MAS score at the wrist ($P < 0.001$, EF=0.224, F=5.64, one-way ANOVA with Bonferroni post hoc test) and finger ($P < 0.001$, EF = 0.236, $F = 5.41$, one-way ANOVA with Bonferroni post hoc test) after the training, and these deductions maintained at the 3-month follow-up assessment.

Subjects No.	**Gender Female/Male**	**Stroke Types Hemorrhagic/ Ischemic**	**Side of Hemiparesis Left/ Right**	**Age (years) Mean ± SD**	**Years after onset of stroke Mean ± SD**
15	3/12	7/8	8/7	57.3±8.87	8.26±4.17

Table 2-1. Demographic characteristics of the stroke subjects (n=15).

Evaluation	Pre 1	Pre 2	Pre 3	Post	3-Month Follow-up	One-way ANOVA	
	Mean (95% Confidence Interval)					P-value (Partial η^2)	F-value
FMA							
Full Score	26.5 (21.1~31.9)	28.3 (22.7~33.8)	29.1 (22.7~35.4)	42.4 (36.3~48.5)	44.2 (38.0~50.3)	.000*** (.313)	7.96
wrist/hand	8.0 (5.4~10.6)	9.1 (6.5~11.6)	9.1 (6.4~11.7)	13.9 (11.4~16.4)	14.3 (11.7~16.9)	.000*** (.228)	5.18
shoulder/elbow	18.5 (15.1~21.9)	19.2 (15.7~22.7)	20 (15.9~24.1)	28.5 (24.5~32.5)	29.8 (26.0~33.7)	.000*** (.320)	8.23
ARAT	14.2 (8.4~20.0)	14.7 (8.2~20.5)	14.7 (8.8~20.5)	27.1 (20.7~33.4)	26.8 (19.4~34.2)	.001** (.226)	5.12
WMFT							
Score	40.5 (29.7~51.2)	40.9 (30.7~51.0)	39.5 (29.5~49.5)	46 (39.2~52.8)	49.3 (42.4~56.2)	.532 (.043)	0.79
Time	50.0 (35.8~64.2)	49.6 (35.6~63.6)	50.5 (36.0~64.9)	39.6 (30.0~49.3)	37.7 (28.2~47.2)	.424 (.053)	0.98
FIM	65.0 (63.8~66.1)	65.8 (65.3~66.3)	65.6 (64.7~66.5)	66.5 (65.8~67.1)	65.7 (64.7~66.7)	.177 (.085)	1.63
MAS							
Elbow	1.7 (1.3~2.1)	1.7 (1.2~2.1)	1.5 (1.0~2.0)	0.8 (0.4~1.2)	0.7 (0.4~1.1)	.002** (.214)	4.77
Wrist	1.6 (1.0~2.1)	1.5 (1.0~2.1)	1.5 (0.9~2.0)	0.6 (0.2~1.0)	0.3 (0.0~0.6)	.000*** (.224)	5.64
Finger	1.5 (1.0~2.1)	1.4 (0.9~2.0)	1.3 (0.8~1.9)	0.5 (0.1~0.8)	0.4 (0.1~0.7)	.000*** (.236)	5.41

Table 2-2. The means and 95% confidence intervals for each measurement of the clinical assessments, and the probabilities with the estimated effect sizes of the statistical analyses. Differences with statistical significance (1-way ANOVA with Bonferroni post hoc tests) are marked with '*' beside the P values. Significant levels are indicated as, * for ≤.05, ** for ≤.01, and *** for ≤.001.

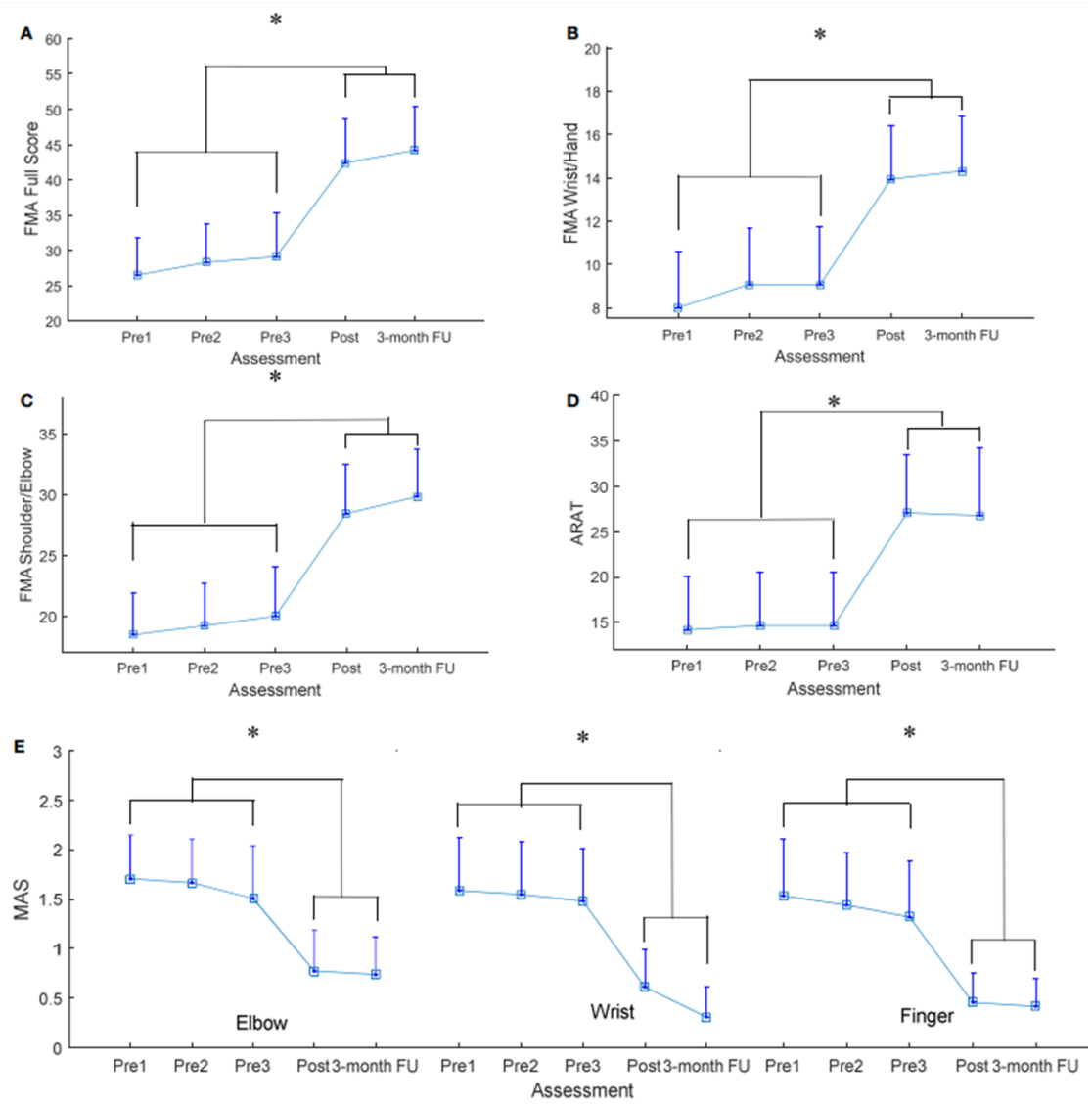

Figure 2-3. The clinical scores measured before, after and 3 months later after the training (A) FMA full score, (B) FMA wrist/hand score, (C) FMA shoulder/elbow score, (D) ARAT score, (E) MAS score at the elbow, the wrist and the fingers, presented as mean value with 2-time standard error (error bar) in each evaluation session. The significant difference is indicated by "*" ($P < 0.05$, 1-way ANOVA with Bonferroni post hoc tests).

Figure 2-4 illustrates the EMG parameters (i.e., the normalized EMG activation level and the normalized CI) that showed statistically significance variations during the evaluation across the 20 training sessions. A significant decrease in EMG activation level was observed in the FD (Figure 2-4A; $P < 0.001$, $EF = 0.331$, $F = 7.29$, one-way ANOVA with post hoc tests) and BIC muscles ($P < 0.001$, $EF = 0.207$, $F = 3.85$, one-way ANOVA with post hoc tests). Regarding the variation patterns of the EMG activation level of the FD muscle, the EMG level showed a rapid decrease of 50% over the first four sessions, and was further declined by 19% from the fifth to twentieth sessions. Concerning the variation patterns of the EMG activation level of the BIC muscle, the EMG level steadily decreased over the 20 training sessions, with a total decrease of 50%. No descending plateau was reached for the EMG levels of the FD and BIC muscles within the 20 training sessions. Figure 2-4B shows the significant decrease in CI of the FD&TRI muscles ($P < 0.001$, $EF = 0.148$, $F = 2.56$, one-way ANOVA with post hoc tests) and BIC&TRI muscle pair ($P < 0.001$, $EF = 0.285$, $F = 5.88$, one-way ANOVA with post hoc tests) during the evaluation across the 20 sessions of the training. Regarding the variation patterns of CI of the FD&TRI muscles and the BIC&TRI muscle pair, the CIs gradually declined and did not reach a plateau over the 20 training sessions. No significant increases or decreases were observed in the EMG parameters of other target muscles and muscle pairs.

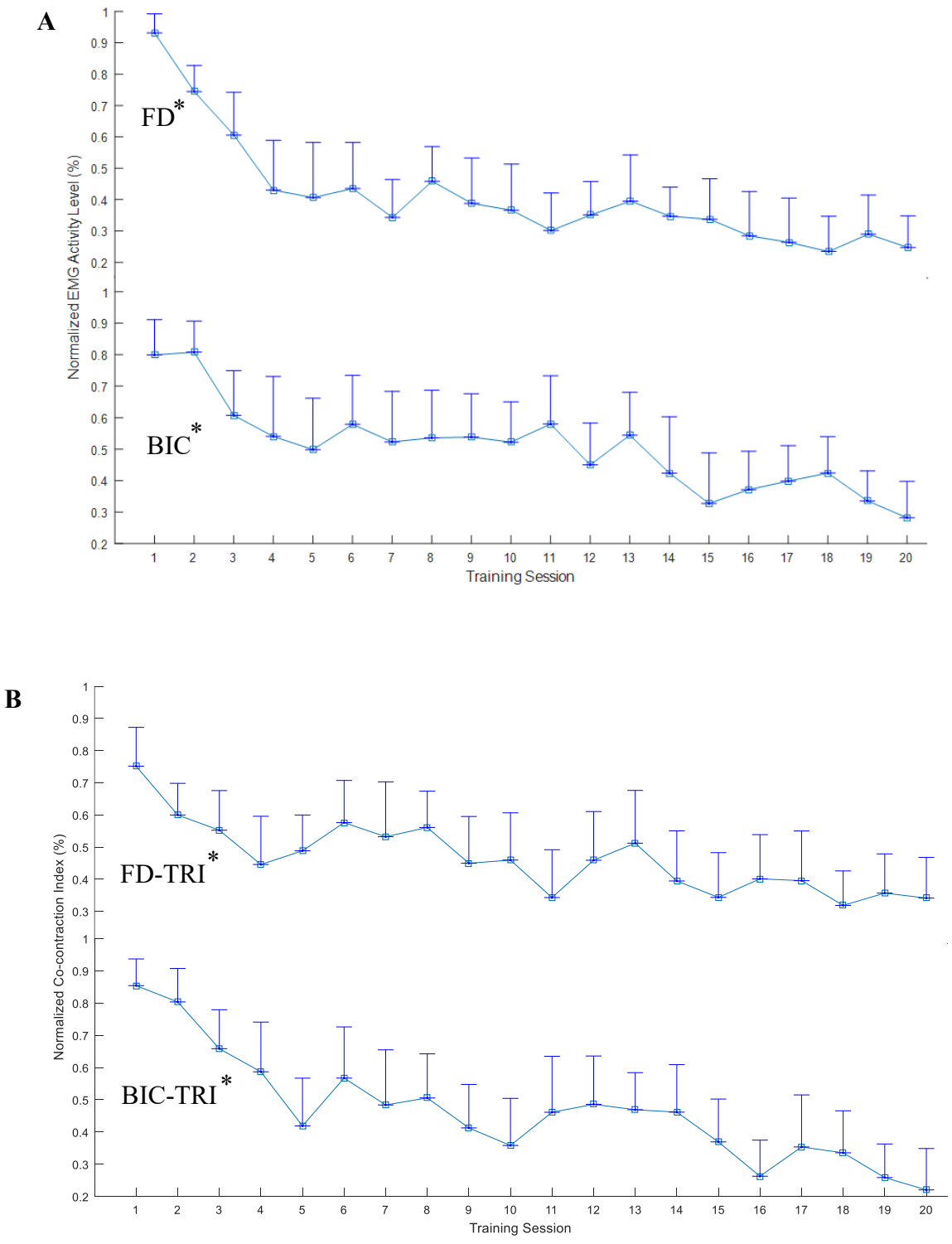

Figure 2-4. The variation of EMG parameters recorded across the 20 training sessions associated with significant decreases indicated by "*" ($P < 0.05$ with 1-way ANOVA with Bonferroni post hoc tests): (A) the normalized EMG activation levels of the FD

and BIC muscles during the bare hand evaluation, and (B) the changes of the normalized CIs of the FD&TRI and BIC&TRI muscle pairs with statistical significance during the bare hand evaluation. The values are presented as mean value with 2-time standard error (error bar) in each session.

2.4 Discussion

In this study, the recruited participants with chronic stroke showed stable baselines without significant variations in all clinical scores before the training. After 20 sessions of the upper limb training assisted with EMG-driven NMES robotic hand, motor function improvements associated with the improved clinical scores and cross-session recorded EMG parameters were observed in all participants and the improvements could maintain for 3-month.

2.4.1 Training effects by clinical assessments

The clinical assessments revealed that the voluntary motor functions and muscle coordination of the paretic upper limb significantly improved after the training. The significant increase in the FMA (shoulder/elbow, wrist/hand) score after the training indicated an improvement in voluntary motor control at the joints of the entire paretic upper limb, and these improvements were maintained at 3-month follow-up assessment. A significant increase of six points in the FMA wrist/hand (max 24) score was found after the training (mean admission score was eight points). Compared with a similar study on robot-assisted hand training using HapticKnob,[42] motor improvement

exhibited a significant increase of one points after the training (mean admission score was eight points). The participants with chronic stroke in both studies practiced hand closing and opening movements through robot-assisted training with comparable training duration and intensity. Hence, the additional improvements in hand functions in this study were probably due to the involvement of voluntary efforts from the paretic limb and NMES during finger extension. The ARAT score is mainly related to finger movements as well as pinching, grasping and gripping movements. The significant increase in the ARAT score suggested improvements in the muscle coordination of the fingers for fine precision grasping and joint stability of the fingers. The significant decrease in the MAS score at the elbow implied a release of flexor spasticity in the elbow joint. The significant decrease in the MAS scores at the flexors of the wrist and fingers indicated that the spasticity of the distal joints was reduced. The muscle tone was graded subjectively by the examiner depending on the amount of the resistance encountered in response to passive movement.[77] A higher MAS score reflects poorer control of synergic muscle activity as well as a tendency to stiffen a limb to compensate for poor control.[71] Stroke survivors usually exhibit various compensatory motions while using their paretic upper limbs.[18] For example, patients with stroke use trunk flexion instead of elbow extension to reach for objects. Similarly, forearm pronation and wrist flexion instead of a neutral forearm position and wrist extension to orient the hand for grasping. The decrease in the MAS scores of the elbow, wrist, and finger joints indicated improved muscle coordination and joint stability of the proximal and distal joints during arm reaching motions as well as during hand grasp and release motions after the training, and these significant improvements maintained for 3-month. In our previous study on the EMG-driven robotic hand assisted upper limb training of patients with chronic stroke,[75] the MAS score of the finger joints decreased by a total of 0.5

points after the training with a mean admission score of 1.3 points. However, in this study, a total decrease of 1 point in the MAS score of the finger joints was demonstrated after the training with a mean admission score of 1.5 points. The additional decrease in the spasticity of the finger joints may be due to the NMES assistance for finger extension during training. Further study was conducted compare the rehabilitation effects of rehabilitation training assisted with the EMG-driven NMES-robotic hand and the EMG-driven robotic hand in a randomized controlled trial.[85] It is reported that both systems could effectively improve the motor functions in distal joints, where the EMG-driven NMES-robot assisted training achieved more release in muscle spasticity and superior voluntary motor recovery and muscle coordination.

A review on robot-assisted post-stroke upper limb rehabilitation[86] indicated that a significant improvement in the function of ADLs (i.e., FIM score) must be associated with a significant improvement in the motor function recovery (i.e., FMA score); however, no study has demonstrated significant improvement in ADL functions without motor recovery. Motor function recovery is considered a prerequisite for the ability to perform ADLs. In this study, significant motor function improvements (i.e., FMA and ARAT scores) have been observed, but the improvements in ADLs were not confirmed using the clinical outcome measures (i.e., WMFT and FIM scores). This might suggest that the motor function improvements after the training might not be transferred to the functional use of the upper limb to perform ADLs, which is a common observation in robot-assisted studies on patients with chronic stroke.[87] This was probably due to the following features in persons with chronic stroke: (1) learned nonuse that could become a habit, and the limb may not be used in functional activities although the individual can move it,[18] and (2) the unaffected limb attempts to execute all motor actions required

for daily living.[88] Further studies should be conducted on upper limb rehabilitation of patients with subacute stroke using the assistance of the EMG-driven NMES robotic hand, which might limit the occurrence of the learned nonuse and increase the functional use of the affected limb in ADLs. In contrast to the WMFT and FIM scores, the FMA, ARAT and MAS scores indicated that significant improvements in arm and hand functions could be maintained 3 months later after the training. This implied that upper limb training assisted with EMG-driven NMES robotic hand could provide motor function recovery for the proximal and distal joints of the impaired limb and support the retentive long-term upper limb rehabilitation for patients with chronic stroke. It was also possible that the participants utilized the affected upper limb more confidently in the daily activities with the improved motor functions after the training, which led to the maintenance of the motor gain 3 months later. However, it did not lead to a significant improvement in the WMFT or FIM.

2.4.2 Training effects by cross-session EMG monitoring

The cross-sessional EMG monitoring reflected the recovery progress of the muscle coordination during the training program, which also monitored individual muscle activation and coordination patterns among the contracting muscles. The significantly improved muscular coordination of the proximal and distal joints also was achieved through the EMG-driven NMES robotic hand assisted training, as revealed by both clinical scores and the EMG parameters (i.e., the normalized EMG activation level and the normalized CI). The decrease in the EMG activation levels could have two major reasons: (1) the reduced spasticity, which reduced the extra muscle activities,[89] and (2) the decreased overactivation of muscles during the initial period of motor learning for

a skill-requiring task.[90] The significant decrease in the EMG activation levels of the FD and BIC muscle reflected the reduced spasticity of the related joints, which was also manifested as the decreased MAS scores in the elbow, wrist, and finger joints. The significant decrease in the normalized EMG activation levels of the FD and BIC muscle across training sessions also reflected a reduction of excessive muscular activities in the FD and BIC muscle in the bare hand evaluation task during hand opening, hand closing, and arm reaching movements. The reduction of excessive muscle activities suggested improved muscle coordination and voluntary motor controls during arm transportation and hand grasp movements. These improvements also contributed to a significant increase in the FMA (shoulder/ elbow, wrist/hand) scores after training. The EMG level of the FD muscle exhibited a rapid decrease of 50 % over the first four sessions, and it further declined by 19% from the fifth and twentieth sessions in contrast to the relatively gradual decrease of the EMG level of the BIC muscle across 20 training sessions, with a total decrease of 50%. These results demonstrated similar patterns in the motor recovery under EMG-driven NMES-robot assisted upper limb training as observed in our previous study on the wrist rehabilitation.[51] In that work, the EMG activation level of the main flexor in the wrist (flexor carpi radialis) decreased faster in a 20-session EMG-driven NMES-robot assisted wrist training program, in comparison with the training only assisted with the EMG-driven pure robot (without NMES). It suggested that the combined treatment of the robot and NMES could speed up the recovery process.[51] In this study, NMES assistance on finger extension may have contributed to the faster release of excessive contraction of the FD muscle, thus further improving muscular coordination of the finger joints. While the results of the EMG levels of the FD muscle showed the acceleration of the recovery process, the EMG levels of the FD and BIC muscles did not reach a plateau within the 20 training sessions.

In a review of motor learning studies, the researcher indicated that the learning of a skilled movement is characterized by a plateau of little or no change in performance.[91] Therefore, the further improvement in the recovery of the FD and BIC muscles could be obtained by providing additional training sessions.

In addition to the EMG activation levels, the CI revealed the co-activity of a muscle pair and the recovery progress on muscular coordination. Dewald et al. indicated that discoordination among muscles is one of the major factors for motor disability after stroke and highly related to the muscle spasticity and compensatory motions in the affected limb.[29] Compensatory movements from proximal joints during motions at distal joints were commonly observed in post-stroke survivors, which resulted in excessive co-contractions in muscles related to both the proximal and distal joints.[62] In this work, the evolutionary patterns of muscular co-activity within a joint and across joints in the upper limb were investigated by CIs among the related muscles. A decrease in the CI value of a muscle pair indicated a release of the co-contraction between the two muscles, i.e., the two muscles could contract more independently in the desired task. The significantly decreased CI of the FD&TRI muscles indicated the reduction of the co-activity between the elbow joint and finger joints which suggested the improved isolation of the distal joint movements from the proximal joint. The reduction in cross-joint muscles (i.e., FD&TRI) also indicated reduced compensation movement from co-contraction on the elbow joint during hand closing and opening motions. The significant decrease in the CI of BIC&TRI muscle pair was observed, and it indicated that the muscle coordination for achieving reaching motions through the elbow flexion and extension was promoted. However, the CI of the FD&TRI muscles and BIC&TRI muscle pair did not reach a plateau within the 20 training sessions. Further decreases in

the CI value could be obtained by conducting additional training sessions.

In this study, the motor function improvements were obtained at the elbow, wrist and fingers as reflected by the clinical scores and the EMG parameters. During the training, the assistance from the EMG-driven NMES-robot was incorporated in the coordinated tasks related to the arm reaching /withdrawing and hand open/close of the whole upper limb. Multi-joint coordinated upper limb practice simulating daily activities is necessary for stroke survivors to regain meaningful motor functions after training, since the task practiced would be the motor function restored, e.g., task-oriented rehabilitation.[92] In the conventional physical rehabilitation on the upper limb, it was hard for a human therapist (or a stroke patient himself/herself in independent practices) to support the arm motions and manage the movements of the distal joints, e.g., finger joints, at the same time. This was one of the reasons that most of stroke survivors experienced reasonable recovery in the proximal joints, whereas little in the distal.[36] In this work, the EMG-driven NEMS-robot managed the finger motions while the stroke participants practicing the whole upper limb tasks, which led to the motor improvements at both the proximal and distal joints. It was also noticed that the motor gains measured by FMA for the shoulder/elbow and wrist/hand were both around 20% immediately after the training (eight-point increment at the shoulder/elbow with a full mark of 42 and five-point increment at the wrist/hand with a full mark of 24). Besides the coordinated physical practice of the upper limb, another reason associated with the proximal recovery was related to the competitive interaction between the proximal and the distal joints in rehabilitation after stroke.[93] Proximal joints (e.g., the shoulder/elbow) could gain more than the distal, e.g., the wrist/fingers, due to the compensatory activities from the proximal joints, which was related to the reduced inhibitory function

of the ipsilesional motor cortex. Physical training at a distal joint benefited the motor function at the proximal joints was also observed in our previous robot-assisted wrist rehabilitation even with a fixed position of the elbow joint.[47, 51]

It was understood that the combined treatment of NMES and robot could induce additional muscle fatigue to the target muscle under stimulation, i.e., the ED muscle in this work, in a training program with multiple sessions. Accumulated fatigue in the stimulated muscle might result in an increase in the EMG amplitude of the target muscle across the sessions. Although normalized EMG signals were adopted in this work to minimize the cross-sessional difference in EMG detection, more sensitive EMG representations which are less affected by the muscle fatigue will be explored in our future study. In this work, there was no significant change observed in the ED EMG level, nor in the CIs related to the ED muscle across the training sessions.

2.5 Periodic Summary

In this study, the training effects of the post-stroke upper limb training assisted with EMG-driven NMES robotic hand were investigated through a single-group clinical trial on patients with chronic stroke. The measured outcomes (i.e., clinical scores and EMG parameters) indicated that significant motor function improvements were achieved after the training, which included an increase in the voluntary motor effort on the entire upper limb, improved muscular coordination, and released muscle spasticity in the proximal and distal joints, and the motor improvements could be maintained for 3-month after the training. The rehabilitation effects of EMG-driven NMES robotic hand were also investigated in a further study, which was a randomized controlled trial of comparison of the rehabilitation effectiveness of EMG-driven NMES robotic hand training and EMG-driven robotic hand training after stroke. Evidence suggests that intensive and repetitive upper limb training with coordinated hand movements assisted by the voluntary EMG-driven NMES robotic hand facilitates hand function recovery and improves muscular coordination in the upper limb with long sustainability in patients with chronic stroke.

CHAPTER 3

AN EXONEUROMUSCULOSKELETON FOR SELF-HELP UPPER LIMB REHABILITATION AFTER STROKE

3.1 Introduction

Upper limb motor deficits are noted in >80% of stroke survivors,[9, 10] who require continuous long-term physical rehabilitation to reduce upper limb impairments.[11, 62] Restoration of poststroke limb function requires intensive repeated training of the paralyzed limb[25, 26] with maximized voluntary motor effort[27, 28] and minimized compensatory motions in close-to-normal muscular coordination.[28, 29] However, long-term poststroke rehabilitation is challenging because of the expanding stroke population and insufficiency of professional staff worldwide.[13, 63] Effective rehabilitation methods with potential for self-help training by stroke survivors are urgently required to improve the independency of stroke survivors and decrease the burden on the healthcare system. Suitable technologies for these methods are currently lacking.[13, 14]

Various rehabilitation robots have been developed to assist the labor-intensive process of physical poststroke training, with main advantages of higher dosage and lower cost compared with traditional “one-to-one” manual-physical therapy.[94] However, these

robots are large equipment powered by alternating current (AC) that require professional operation in a clinical environment with limited access to outpatients. Mobile exoskeletons are an emerging technology with wearable application. These exoskeletons are powered by portable batteries and have potential for user-independent self-help rehabilitation that can be accessed anytime, even in unconventional environments (e.g., at home).[14, 56, 57] However, currently available upper limb exoskeletons, which are composed of rigid materials and actuated by electrical motors, are constrained by their heavy weight and low torque-to-weight ratio, which limit their user-independent applications. These exoskeletons require high power consumption because their actuations must generate sufficient torque to support paralyzed limbs as well as weight of the system worn on the body. Thus, most exoskeletons require AC supply,[13, 57, 58] which triggers electrical safety concerns for user-independent usage. Furthermore, the body-device integration is neither stable nor comfortable in current rigid exoskeletons, with misalignment or migration occurring during repeated practice mainly because of the non-negligible weights mounted onto the paretic limb.[13, 56] Misalignments with additional loads deteriorate abnormal muscular coordination in the paralyzed upper limb, which undermines the rehabilitative potential of the aforementioned systems.[95, 96] Therefore, most rigid exoskeletons for poststroke upper limb rehabilitation are still used under the close assistance of professionals in clinical environments, and their rehabilitation effects in user-independent operations are unclear.

With the introduction of soft materials in mechanical actuation, soft robotic equipment has been designed using easily deformable materials with light and flexible actuators that conform to human body contours[59, 97-99] so as to achieve superior body-device integration to that provided by rigid robotic equipment. Three main types of actuation systems, namely cable, hydraulic, and pneumatic systems, are used in current wearable

soft robots.[59] Cable systems used cables with desired tension attached to a target limb for flexion/extension.[13, 60] The cable-driven upper-limb exoskeletons usually have a lightweight design with low inertia in the wearable part accommodating possible joint misalignment between the paretic limb and the exoskeleton.[60] However, the cable is driven by electric motors with gears/pulleys, leading to an increment of complexity and overall weight of the whole assembly.[60] Hydraulic systems are powered by hydraulic pressure, and able to produce greater torque compared to the actuators in cable and pneumatic systems.[13, 60, 100] However, few hydraulic systems have been developed for upper limb, because they are relatively heavy and complex in the design, requiring additional space to accommodate the fluid and to prevent leakages under pressure.[13, 58, 60] In contrast, pneumatic systems (pneumatic muscles) are the most commonly adopted actuation for the upper limb.[59, 60] Pneumatic exoskeletons have high torque-to-weight ratios because of the low weight of the wearable part actuated by air.[59, 101-105] However, pneumatic systems are usually bulky and slow in power transmission from pressure to torque during air inflation by compressors for needed air volume and pressure compared with electrical motor actuation in rigid exoskeleton to achieve equivalent mechanical outputs (e.g., joint torque).[60, 61] Large and high-power compressors connected to the pneumatic muscles constrain these devices for user-independent applications.[59] Thus, a novel lightweight mechanical design is required to achieve optimized body-device integration with fast power transmission, high torque-to-weight ratios, and low power consumption for user-independent self-help rehabilitation.

Neuromuscular electrical stimulation (NMES), proposed for upper limb rehabilitation,[32, 33] can activate the contraction of impaired muscles to generate limb movement[32, 33] and effectively enhance the muscle force and sensory feedbacks for motor relearning after stroke.[35] However, controlling motion kinematics, such as the

range of motion (ROM) and trajectory, by using NMES alone is difficult because of the limited stimulating precision in fine motor control.[106] Recently, NMES has been combined with mechanical robots in poststroke training. [48] The combined NMES-robot treatment is more effective than treatment involving the use of only NMES or only a robot in upper limb rehabilitation, particularly in improving the muscular coordination by reducing muscular compensation.[34] The integration of NMES into a robot can trigger the biological actuation of target muscles to reduce the demand of mechanical support from the robot part.[13] However, little has been done on the integration of NMES with mobile exoskeletons or soft robots.

In this study, we designed a multi-integrated robotic system that combines the NMES, soft pneumatic muscle, and exoskeleton techniques, namely exoneuromusculoskeleton, for upper limb rehabilitation after stroke. Mechanical integration between rigid exoskeleton and pneumatic muscle (i.e., exomusculoskeleton) can enable high torque-to-weight ratios with a compact size and fast power transmission. By combining NMES with the exomusculoskeleton (i.e., exoneuromusculoskeleton), the mechanical scale and power-requirement of the entire system can be reduced due to the evoked muscular effort. In addition, NMES and mechanical assistance enable the achievement of close-to-normal muscular coordination with minimized compensatory motions. To optimize therapeutic outcomes, electromyography (EMG) of the paralyzed limb has been used to indicate voluntary intentions[46] to maximize voluntary motor effort during practice for better improvements in voluntary motor functions with longer sustainability compared with those with passive limb motions.[47] In this study, we designed an EMG-driven exoneuromusculoskeleton to assist the upper limb physical practice at the elbow, wrist, and fingers. The assistive capability of the designed system was evaluated on patients with chronic stroke. The designed system's feasibility of self-help operation

and rehabilitation effects were also investigated through a pilot single-group trial.

3.2 Methods

The designed exoneuromusculoskeleton (Figure 3-1) could be worn on the paretic upper limb of a stroke survivor. The designed system comprised two wearable parts: the elbow (158 g) and wrist/hand (50 g). Both parts were connected to a pump box (80 g) mounted on the upper limb. Moreover, a control box (358 g) that included system control circuits and a rechargeable 12-V battery could be carried on the waist. The developed system can assist a stroke survivor to perform sequential arm reaching and withdrawing tasks, namely (1) elbow extension, (2) wrist extension with the hand open, (3) wrist flexion with the hand closed, and (4) elbow flexion. Real-time control and wireless communication between the control box and a mobile application (app) were achieved on a smartphone through a microprocessor and Bluetooth module.

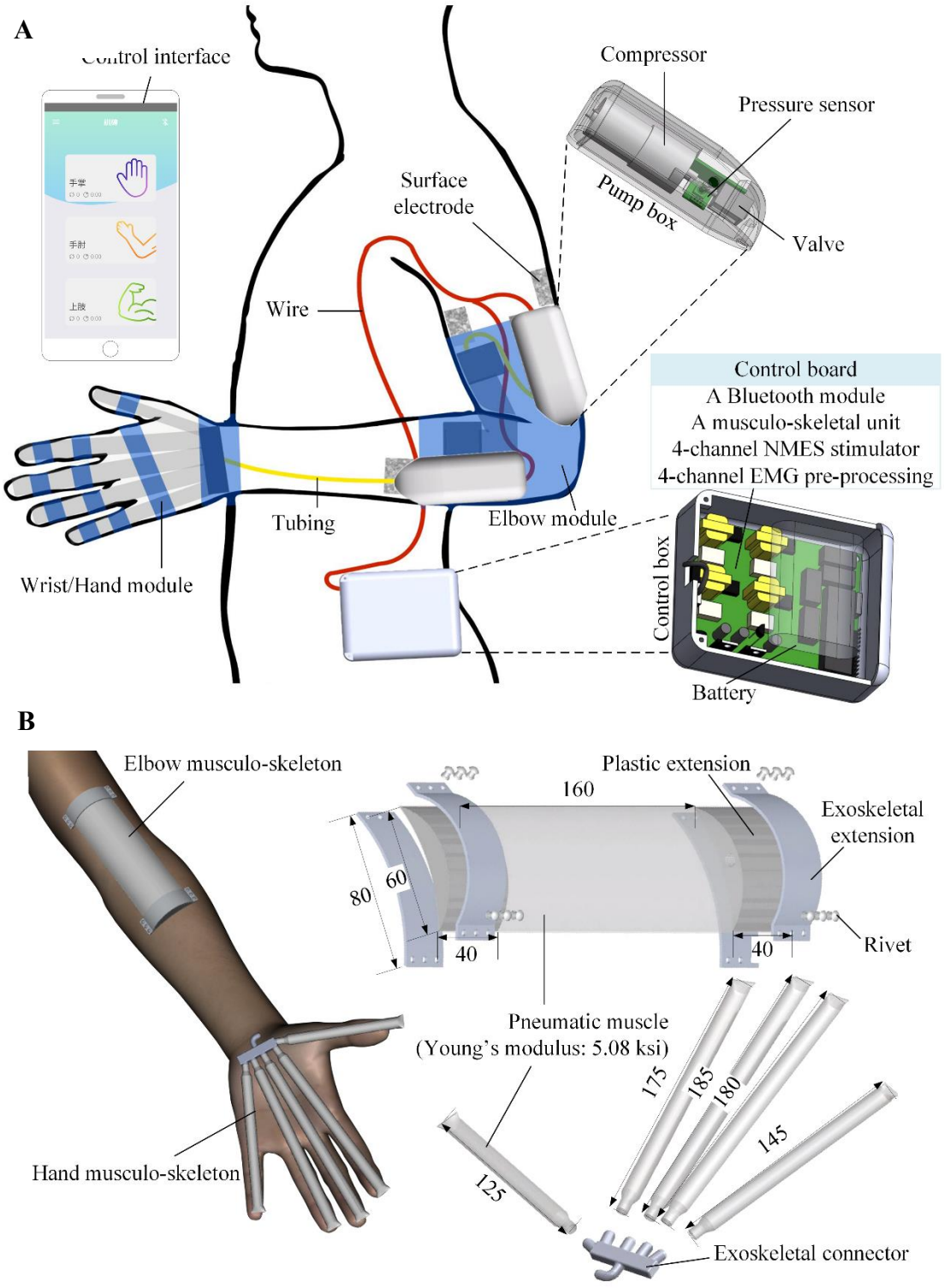

Figure 3-1. (A) Overview of the exoneuro-musculoskeleton, with the inner structures of a pump and the control box. (B) Attachment of the musculoskeletons, and structures with dimensions of the elbow musculoskeleton and the hand musculoskeleton (all the dimensions are in millimetres).

3.2.1 System control platform

Figure 3-2A depicts the system control diagram of the exoneuromusculoskeleton system. The system comprised a microcontroller unit (MCU), a musculoskeletal unit, an NMES compartment, a channel switch module, and an EMG pre-processing module. The MCU (PIC18F46K22, Microchip Technology Inc., Chandler, Arizona, USA) coordinated with a musculoskeletal unit, 4-channel NMES stimulator, 4-channel EMG pre-processing, and wireless communication with the developed app through a Bluetooth module (Bluetooth HC-05, JMoon Technologies., New Delhi, India). The musculoskeletal unit comprised elbow module and hand module for providing mechanical assistance. Each module included a related musculoskeleton, connected to a respective miniature air compressor (P54A02R, Oken Seiko Co., Ltd., Tokyo, Japan) with a valve and pressure sensor (BMP series, Adafruit Inc., NYC, NY, USA). The air compressor was used to inflate the musculoskeleton, which would deflate when the valve was opened. The inflated musculoskeleton provided mechanical torque to a joint during extension and it deflated passively during flexion. The NMES compartment provided electrical stimulation (square pulse with adjustable pulse width of 0-300 μs, 70 V, 40 Hz)[107] to the muscle of the biceps brachii (BIC) during elbow flexion, muscle of the triceps brachii (lateral head, TRI) during elbow extension, muscle union of the flexor carpi radialis (FCR) and the flexor digitorum (FD) during wrist flexion with the hand closed, and muscle union of the extensor carpi ulnaris (ECU) and the extensor digitorum (ED) during wrist extension with the hand open.[108] The activation of the musculoskeletons and NMES were controlled by the EMG signals detected for the BIC muscle, TRI muscle, FCR-FD muscle union, and ECU-ED muscle union in different motion phases. In this study, EMG detection and NMES delivery to a target muscle

were performed using a pair of surface electrodes (5×5 cm^2, PALS Neurostimulation Electrodes, Axelgaard Manufacturing Co., Ltd., Fallbrook, CA, USA) connected to an EMG-NMES channel. An electrode pair was placed on the motor point at the muscle belly for achieving effective EMG capture and NMES delivery, as achieved in Muraoka's work.[109] Because of the close anatomical proximity between the FCR and FD muscles and between the ECU and ED muscles, electrode pairs were located in the common area of the motor point of the two muscle bellies of the FCR-FD and ECU-ED muscle unions.[108] A channel switch circuit was integrated into each EMG-NMES channel and used to alter the functions between the input of the EMG detection and the output of the NMES through the same electrode pair. This circuit also protected the EMG amplification circuit from the high stimulation voltage.[109, 110] A reference electrode (2 × 3 cm^2, Blue Sensor N, Ambu Inc., Ballerup, Denmark) was attached to the skin surface of the olecranon for reducing the common mode noise. The EMG signals captured using the surface electrodes were first amplified 1000 times (preamplifier: INA 333; Texas Instruments Inc., Dallas, TX, USA) and filtered from 10 to 500 Hz. These amplified and filtered signals were then sampled using an analog-to-digital converter (AD73360, Analog Devices Inc., Norwood, MA, USA) with a sampling frequency of 1000 Hz for each EMG channel. Digitized EMG data were retrieved using a digital signal controller (dsPIC33F, 16bit, Microchip Technology Inc., Chandler, Arizona, USA) for further manipulation by the MCU. After digitization, the EMG signals were full-wave rectified and moving-averaged with 100-ms window to obtain the EMG levels.

3.2.2 EMG-drive control

EMG-triggered control was adopted in this study.[75, 111] In other words, voluntary EMG

from a target driving muscle was used to initiate assistance from the developed system. Once the EMG level of a driving muscle or muscle union reached a preset threshold, exoneuromusculoskeletal assistance (i.e., musculoskeleton and NMES) was initiated and continuously provided during an entire motion phase. In each motion phase, a patient was also required to exert the residual voluntary effort, together with the exoneuromusculoskeletal assistance to achieve the desired motion. The controlling workflow of the EMG-driven exoneuromusculoskeleton assisted in phasic and sequential limb tasks is shown in Figure 3-2B. The assistance scheme of the developed system was defined as follows for the coordinated multi-joint limb tasks:

$$Exoneuromusculoskeletal\ assistance = \begin{cases} V_{EMG,TRI} \cdot Assistance_{elbow}(NMES + Musculoskeleton\ Inflation), \\ in\ elbow\ extension \\ V_{EMG,ECU-ED} \cdot [Assistance_{wrist}(NMES) + Assistance_{fingers}(NMES + Musculoskeleton\ inflation)], \\ in\ wrist\ extension\ \ hand\ open \\ V_{EMG,FCR-FD} \cdot [Assistance_{wrist}(NMES) + Assistance_{fingers}(NMES + Musculoskeleton\ deflation)], \\ in\ wrist\ flexion\ \ hand\ closed \\ V_{EMG,BIC} \cdot Assistance_{elbow}(NMES + Musculoskeleton\ Deflation), \\ in\ elbow\ flexion \end{cases} \quad \text{(Eq. 1)}$$

where three times the standard deviation (SD) above the EMG baseline in the resting state was set as a threshold level in each motion phase. When the EMG level of a driving muscle or muscle union m reached a preset threshold, the value of $V_{EMG,m}$ was 1 and assistance was simultaneously triggered from both the musculoskeleton and NMES to assist the extension or flexion of the related joint. When the EMG level did not reach the preset threshold, the value of $V_{EMG,m}$ was 0. The parameter $Assistance_{elbow}(NMES + Musculoskeleton\ Inflation)$ is the assistance provided during elbow extension, including the NMES (with a threshold pulse width to evoke visible elbow extension)[74] applied to the TRI muscle and the mechanical extension torque provided to the elbow joint by the inflated elbow musculoskeleton. The parameter $Assistance_{wrist}(NMES) +$

$Assistance_{fingers}(NMES + Musculoskeleton\ inflation)$ is the assistance provided during wrist extension with the hand open, including the NMES (with a threshold pulse width to evoke maximal wrist extension with full finger extension)[74] applied to the ECU-ED muscle union and the mechanical extension torque provided to the fingers by the inflated hand musculoskeleton. The parameter $Assistance_{wrist}(NMES) + Assistance_{fingers}(NMES + Musculoskeleton\ deflation)$ is the assistance provided during wrist flexion with the hand closed, including the NMES (with a threshold pulse width to evoke maximal wrist flexion with full finger flexion)[74] applied to the FCR-FD muscle union and the hand musculoskeleton could be deflated passively during the aforementioned assistance. Most stroke survivors could perform voluntary finger flexion but most of them cannot extend their fingers.[112] The residual voluntary effort from the finger flexors of the paretic limb would facilitate the release of the air from the musculoskeleton in deflation. The parameter $Assistance_{elbow}(NMES + Musculoskeleton\ Deflation)$ represents the assistance provided during elbow flexion, including the NMES (with a threshold pulse width to evoke visible elbow flexion)[74] applied to the BIC muscle and the elbow musculoskeleton could be deflated passively during the aforementioned assistance. Meanwhile, the residual voluntary effort from the elbow flexors of the paretic limb would facilitate the release of the air from the musculoskeleton in deflation.

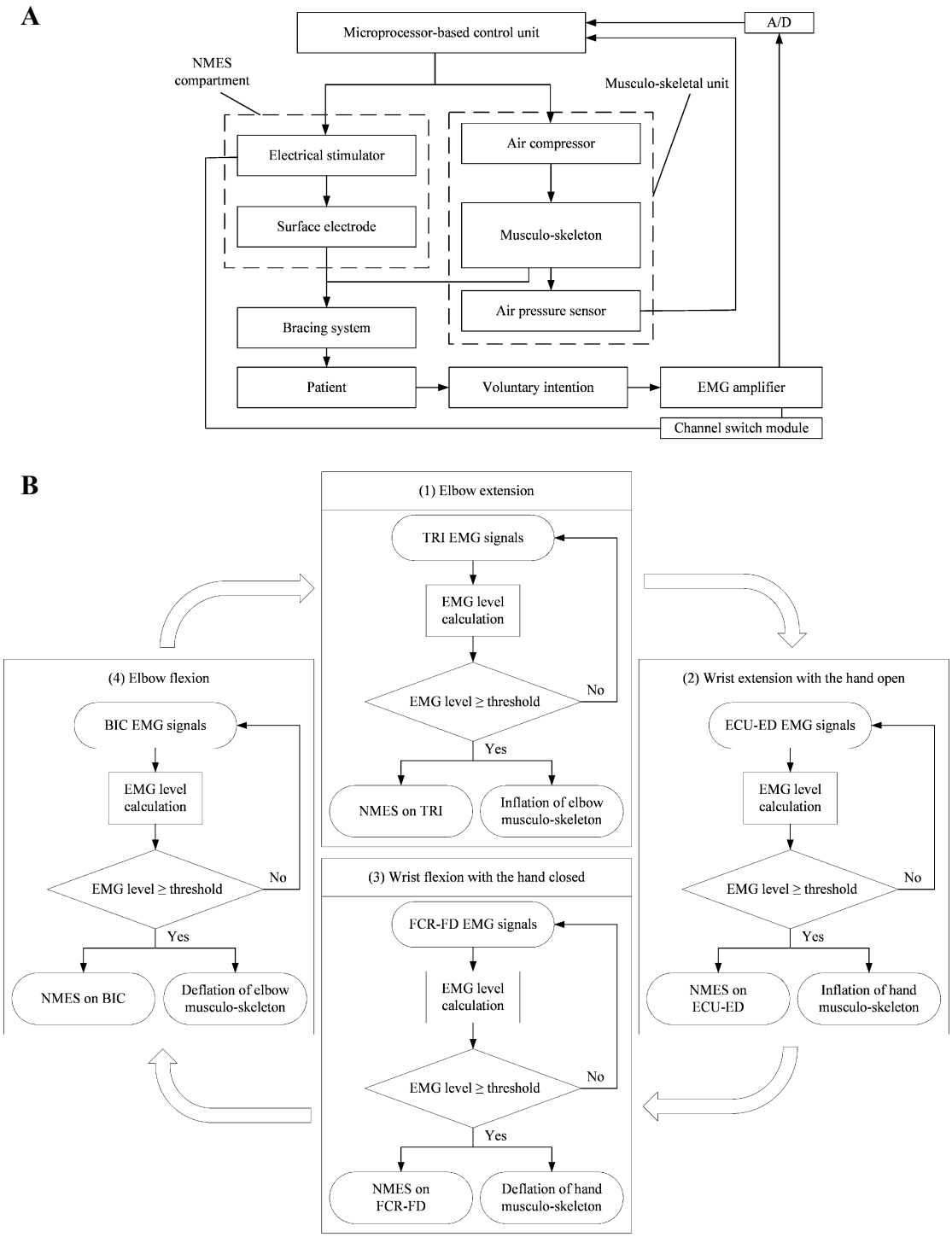

Figure 3-2. (A) The schematic diagram of the control in the EMG-driven exoneuromusculoskeleton, and (B) the controlling workflow of the assistance in phasic and sequential limb tasks.

3.2.3 Mechanical structure of the musculoskeletons

The elbow musculoskeleton, which had a length of 24 cm (the detailed dimensions are presented in Figure 3-1B), was composed of one piece of pneumatic muscle (polyvinyl chloride (PVC) membrane, 1-mm thick) in the middle and an exoskeletal extension at each end. The musculoskeleton provided extension torque when the pneumatic muscle was inflated by the air compressor. A three-dimensional (3D) printed plastic (photopolymer) extension (height: 4 cm, width: 6 cm, and thickness: 1 cm) was connected and sealed at each end of the pneumatic muscle. The connections were pressed with two aluminum plates and fastened using rivets. The elbow musculoskeleton was attached to the ventral side of the elbow, with its geometric center located at the joint on the paretic arm around which an elastic sleeve-like bracing (spandex) was wrapped. The musculoskeletons were integrated inside of an elastic bracing (spandex) with the purpose to achieve an average pressure applied to the skin surface from 1279 to 2860 Pa during the inflation and deflation of the pneumatic muscles for the needed mechanical assistance, as well as stable and comfortable wearing experience.[113, 114] The hand musculoskeleton (Figure 3-1B) comprised five pneumatic finger muscles (PVC membrane, 1-mm thick), one for each digit (width of 1.6 cm for each pneumatic muscle; thumb length = 12.5 cm, index finger length = 17.5 cm, middle finger length = 18.5 cm, ring finger length = 18.0 cm, and little finger length = 14.5 cm) that converged to a 3D printed exoskeletal connector (photopolymer) at the end of the musculoskeleton, which connected to the air compressor. Each pneumatic finger muscle generated extension torque for the fingers during inflation. The hand musculoskeleton was embedded in an elastic glove-like bracing (spandex) and fixed on the palm during hand opening or closing movements, with the exoskeletal connector

located near the bottom of the palm. The maximal inner pressures of the pneumatic muscles of both musculoskeletons were set at <100 kPa to maintain the stability of the musculoskeletons under repeated inflations and deflations. The proportions and lengths of the musculoskeletons were selected according to mean values of the upper limb anthropometrics for Asian adults.[115, 116]

3.2.4 Pressure-torque transmission of the musculoskeletons

The pressure-torque transmission properties of the musculoskeletons were quantified by determining the relationship between the inner pressure and extension torque of the musculoskeletons. The pressure-torque transmission rate was determined as the response time of each musculoskeleton for achieving a preset maximal inner pressure. The musculoskeletons for the elbow and hand were evaluated separately in this study.

3.2.4.1 Elbow module

The experimental setup for measuring the pressure-torque transmission of the elbow musculoskeleton during extension is depicted in Figure 3-3A. One end of the skeletal extension was fixed on a platform, with half the length of the musculoskeleton falling outside the platform. The configuration in Figure 3-3A was used to evaluate the extension torque provided to the elbow joint, when the elbow musculoskeleton was attached to the elbow and extended around the center located at the elbow joint. The musculoskeleton was inflated by the compressor with the fully opened valve till the inner pressure reached 95 kPa, at which the elbow musculoskeleton was fully extended to 180°. Then, a weighed loading (sandbag) was hanged to the unfixed end of the exoskeletal extensions. The total hanging weight increased until the musculoskeleton

flexed at the joint position with an angle of 170° because most chronic stroke patients with muscle spasticity can reach 170° of the elbow joint passively.[117] When adding the load, the inner pressure was maintained at <100 kPa. The change in the joint angle was measured using a protractor whose midpoint was aligned with the rotation center of the musculoskeleton. The total weight of loading and the corresponding reading of the inner pressure were recorded. The inner pressure of the musculoskeleton was then decreased in steps of 5 kPa with an error within 1 kPa. The measuring scale was set from 5 to 95 kPa without loading in this study because a minimum inner pressure of 5 kPa was required to achieve a joint angle of 180° for the elbow musculoskeleton under free loading. The measurement was repeated three times for each scaling step. A similar evaluation method was adopted in a study on a pneumatic elbow sleeve.[118] The produced output torque related to each measured pressure was calculated as follows:

$$Torque = L \cdot cos10° \cdot W \qquad \text{(Eq. 2)}$$

where L is the length between the axis of rotation and the endpoint of exoskeletal extension with loading and W is the weight of the loading.

The response time of the elbow musculoskeleton during inflation was recorded under free loading. The response time was used to measure the baseline performance of the elbow module before the module was used to provide joint assistance to humans. The musculoskeleton was fixed on a platform with the configuration depicted in Figure 3-3A. The musculoskeleton was then inflated from an inner pressure of 0 kPa to <100 kPa without external loading with the fully opened valve. The measurements were repeated thrice.

3.2.4.2 Hand module

The pressure-torque transmission of the hand module was assessed using the middle finger as a representative finger for the measurement of the pressure-torque relationship (Figure 3-3B). The middle finger was considered as the representative finger because it has the longest extended length and largest air volume among the fingers in the evaluation of the finger extension torque of the musculoskeleton. The configuration in Figure 3-3B was used to evaluate the extension torque provided to the metacarpophalangeal (MCP) joint of the middle finger when the musculoskeleton was attached to the palm and extended around the center located near the MCP joint, which was the primary joint when the hand was open.[119] The exoskeletal connector of the hand module was fixed on the platform with the pneumatic middle finger, which was present in the palm area inside the platform. The length of the middle finger musculoskeleton inside the platform was 11 cm, which represents the mean length of the wrist joint and MCP joint of the middle finger on the palmar side of Asian adults.[116] The hand musculoskeleton, including all the pneumatic fingers, was inflated and deflated simultaneously during the experiment. The procedures for the pressure-torque measurement performed on the middle finger musculoskeleton and the response time measurement performed on the hand musculoskeleton having the configuration depicted in Figure 3-3B were similar to those used to assess the pressure-torque relationship and response time of the elbow musculoskeleton.

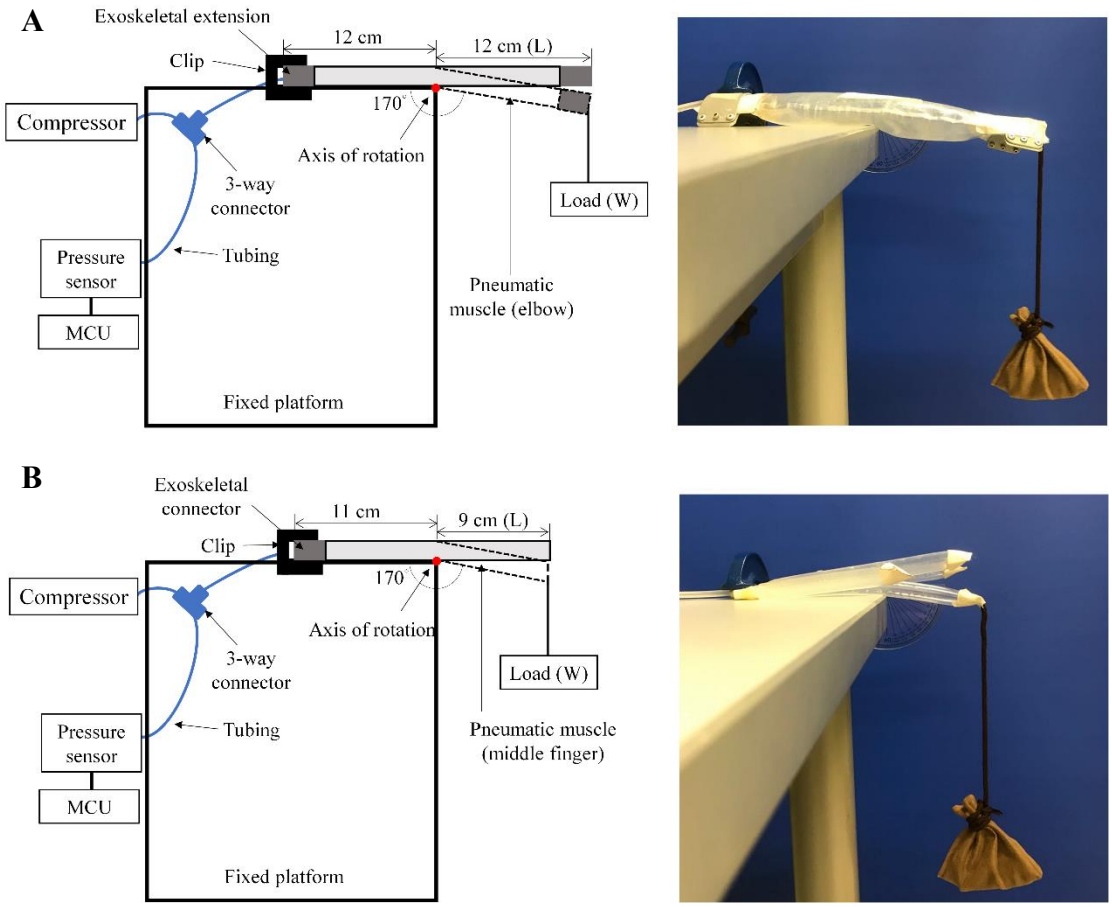

Figure 3-3. Experimental setup for the evaluation of the pressure-torque transmission properties of the musculoskeleton for the (A) elbow and (B) hand.

3.2.5 Evaluation of joint assistance by the EMG-driven exoneuromusculoskeleton

The assistive capability of the EMG-driven exoneuromusculoskeleton was evaluated on patients with chronic stroke by using four assistance schemes, as presented in Table 3-1, to understand the different assistance contributions of NMES and the musculoskeleton to the upper limb movements. After obtaining ethical approval from the Human Subjects Ethics Subcommittee of the Hong Kong Polytechnic University,

10 participants with chronic stroke were recruited for the evaluation. The demographic data of the participants in the evaluation are presented in Table 3-2. Written informed consents were obtained from all the recruited participants in this study. The inclusion criteria were as follows: (1) at least 1 year after the onset of a singular and unilateral brain lesion due to stroke; (2) the spasticity at the elbow, the wrist and the fingers were ≤3 as measured by the Modified Ashworth Scale (MAS);[77] (3) motor impairments in the affected upper limb range from severe to moderate according to the Fugl-Meyer Assessment (FMA; 15 < FMA < 45, with a maximal score of 66 for the upper limb);[40] (4) presence of no visual deficit and the ability to understand and follow simple instructions, as assessed by the Mini-Mental State Examination (MMSE > 21);[78] (5) presence of detectable voluntary EMG signals from the driving muscle on the affected side (three times the SD above the EMG baseline); and (6) presence of passive ROM for the wrist from 45° extension to 60° flexion, presence of passive ROM for the elbow from 30° to 170°, and ability of the MCP finger joints to be passively extended to 170°.

Notation of assistance schemes	**Description**
N0M0	No assistance from either the musculoskeleton or the NMES
N1M0	Assistance from the NMES only
N0M1	Assistance from the musculoskeleton only
N1M1	Assistance from both the musculoskeleton and the NMES

Table 3-1. Notations for the different assistance schemes of the Exoneuromusculoskeleton.

Subjects No.	Gender Female/Male	Stroke Types Hemorrhagic/ Ischemic	Side of Hemiparesis Left/ Right	Age (years) Mean ± SD	Years after onset of stroke Mean ± SD
10	4/6	4/6	6/4	64.1±5.89	5.60±3.98

FMA Mean ± SD	MAS Elbow Mean ± SD	MAS Wrist Mean ± SD	MAS Finger Mean ± SD
37.2±11.6	1.46±0.39	1.54±1.19	1.44±0.91

Table 3-2. Demographic characteristics of the participants recruited for the ROM measurements (n=10).

3.2.5.1 Evaluation

The evaluation comprised three sessions for the measurement of assistive performance of the developed system for the elbow, wrist, and finger joints. The performance of each joint was evaluated according to the ROM achieved under different assistance schemes (Table 3-1).

3.2.5.1.1 Elbow and wrist sessions

The ROMs related to the elbow and wrist joints were measured separately through motion capturing. In total, 25 spherical reflective markers (12-mm diameter for each) were attached to the skin with double-sided tape according to the upper limb model of the BodyBuilder model (Vicon Motion Systems, Oxford, UK).[120] The marker positions were captured through an eight-camera motion system (Vicon Motion Systems, Oxford, UK), with a sampling frequency of 250 Hz. A Vicon Workstation (Vicon Motion Systems, Oxford, UK) with 3D reconstruction software (Vicon Nexus and BodyBuilder, Oxford, UK) was used to anatomically label, filter, and apply the upper limb model.[120-

[122] The dynamic joint angles during motion were thus obtained during all trials.[123] The ROMs of the target joints in the extension phase were investigated because most patients with chronic stroke experience impairment in joint extension in the upper limb rather than in flexion.[112] Most of the poor limb performance (e.g., open hand to grasp) was related to an inability to activate extensor muscles on the upper limb.[124]

In the elbow session, the participants wore the elbow module on the affected limb and sat on a 45-cm-high straight-back chair in front of a 72-cm-high table (Figure 3-4A). The tested arm was positioned using an upper arm fixer on a lifting shelf placed near the table edge. In the initial position, the forearm was pronated and the shoulder was positioned at 80° vertical abduction with approximately 10° flexion. The participants' unaffected hand rested on their thigh. The participants were required to perform a task that involved placing their elbow at approximately 90° initially and then extending their elbow to their maximal angle. The participants were instructed to complete the task at their natural speed after the experiment operator provided them an audio starting signal. The trial was completed when they reported that they had achieved their maximal elbow extension or when the inner pressure of the elbow musculoskeleton reached 100 kPa. All the participants reported the completion of the trial before the inner pressure reached 100 kPa within 25 s. The recorded trial lengths were sorted in ascending order from 0 to 21 s and used for comparing the response time in the elbow session because a stable value (defined as <1% change in the maximum value) was achieved within 21 s in all the trials.

In the wrist session, the participants wore the wrist/hand module on the affected limb and sat on the same chair as in the elbow session (Figure 3-4B). The table used in the wrist session was also the same as that used in the elbow session. The tested arm was

positioned using a forearm fixer and a splint that attached to the table edge. The shoulder was positioned at 20° lateral rotation with approximately 30° vertical abduction. The elbow was positioned with a joint angle of 140°, and the unaffected hand rested on the thigh. The participants were required to conduct a wrist task that involved placing the wrist at approximately 0° initially (i.e., the neural position for extension or flexion) and then extending the wrist to their maximal angle. After the experiment operator provided an audio starting signal, the participants were required to perform the task at their natural speed. The trial was completed when they reported that the maximal wrist extension was reached or when the inner pressure of the hand musculoskeleton reached 100 kPa. Although the wrist movement was only supported by NMES in this study, four assistance schemes (Table 3-1) were used in the evaluation of the ROM of the wrist joint because the assistance provided by the exoneuromusculoskeleton for the wrist was triggered in conjunction with that for the fingers in the same motion phases (i.e., wrist extension with the hand open and wrist flexion with the hand closed) during limb practice. The developed system assisted coordinated movements between the wrist and the fingers for the participants in this study. Moreover, a study reported that the wrist ROM can be affected by finger positions.[125]

All the participants reported the completion of the trials within 16 s. The recorded trial lengths were sorted in ascending order from 0 to 13 s and used for comparing the response time in the wrist session because all trials reached a stable value in <13 s.

The ROM of each joint in the task was measured by comparing the final and initial joint angles. The participants performed the task three times with each assistance scheme (Table 3-1) in random order. Thus, each participant performed 12 trials in each session.

A 1-min rest period was provided between two consecutive trials to prevent fatigue.

3.2.5.1.2 Finger session

The finger ROMs were obtained through manual goniometric measurements because the main impairment in the hand for patients with chronic stroke is hand opening, during which fingers flex passively due to spasticity in the finger flexors.[112] Attaching markers on the spastic finger joints of the recruited participants was not feasible.

In the finger session, the participants wore the wrist/hand module on the affected limb and sat on a 45-cm-high straight-back chair in front of a 72-cm-high table. The tested hand was fixed 12 cm from the table edge in the midline of an acrylic shelf with straps. The participants' other hand rested on their thigh. The wrist was positioned at approximately 0° during the evaluation of the MCP, proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints of the index, middle, ring, and little fingers (Figure 3-4C). When conducting measurements on the MCP and DIP joints of the thumb, the hand was pronated and the wrist was positioned at approximately 0° (Figure 3-4D). The aforementioned configurations were used to minimize the gravity effect on the finger movements. During the measurements, the participants were required to perform their maximal flexion and extension for each joint at their natural speed in a trial. A trial was initiated when the participants reported that they had reached their maximal flexion and was completed when the participants reported that they had achieved their maximal extension or when the inner pressure of the hand musculoskeleton reached 100 kPa. A video camera was used during the measurement, and videos were recorded at a frame rate of 30 fps to confirm the movement timing in each trial. All the participants reported the completion of the trials within 12 s before

the inner pressure reached 100 kPa. The finger joint angles were obtained manually by placing the axis of a finger goniometer on the dorsal part of each joint.[126] Each joint was measured thrice with the four assistance schemes in random order. Thus, 12 trials were performed for each joint. A 1-min rest period was provided between two consecutive trials to prevent fatigue. The ROM of each measured finger joint was recorded by measuring the angles between the beginning position (i.e., at a maximal flexion angle) and the final position (i.e., at a maximal extension angle) in a trial. In addition to the ROM of each measured finger joint, the ROM of each finger (SUM_ROM) was defined as the sum of the ROMs of its measured joints (i.e., the MCP, PIP and DIP joints for the index, middle, ring, and little fingers and the MCP and DIP joints for the thumb).

Each participant was required to complete all the elbow, wrist, and finger sessions on the same day. A 20-min break was provided between two consecutive sessions to avoid fatigue. Figure 3-4E illustrates the evaluation protocol presented with timeline.

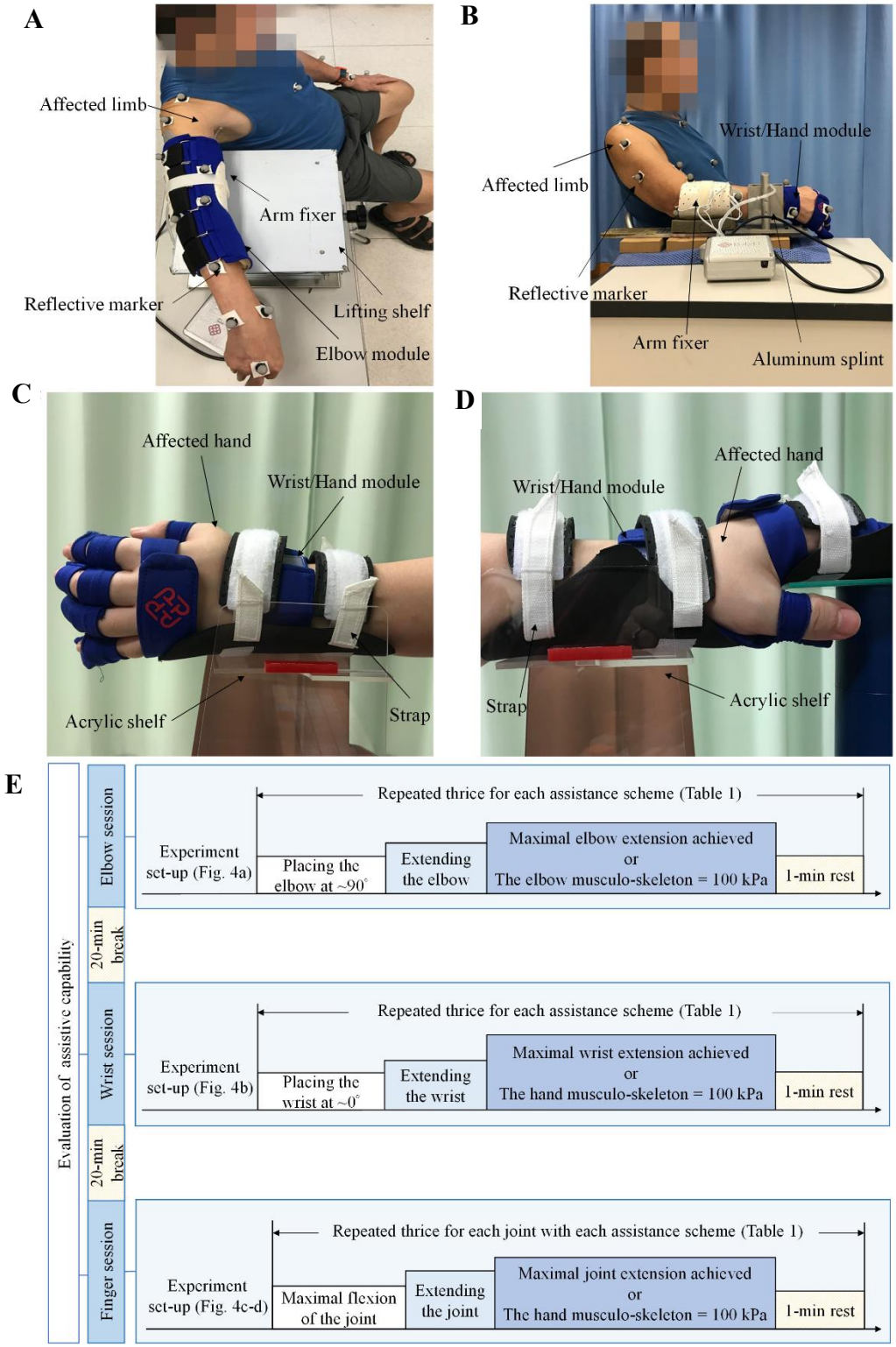

Figure 3-4. Seating configuration during the evaluations in the (A) elbow and (B) wrist sessions as well as the experiment setup of finger joint goniometric measurements for the (C) index, middle, ring, and little fingers and (D) thumb, and (E) the evaluation

protocol presented with timeline.

3.2.6 Self-help upper limb training assisted by the EMG-driven exoneuromusculoskeleton

A pilot clinical trial with a single-group design was conducted to investigate the feasibility and rehabilitation effects of self-help upper limb training assisted with the EMG-driven exoneuromusculoskeleton. A total of 15 participants with chronic stroke who met the same inclusion criteria as in the aforementioned evaluations were recruited in the pilot trial after obtaining ethical approval from the Human Subjects Ethics Subcommittee of the Hong Kong Polytechnic University. The demographic data of the participants in the pilot clinical trial is presented in Table 3-3. Written consent was obtained from each participant prior to clinical trial commencement.

Subjects No.	Gender Female/Male	Stroke Types Hemorrhagic/ Ischemic	Side of Hemiparesis Left/ Right	Age (years) Mean ± SD	Years after onset of stroke Mean ± SD
15	5/10	8/7	7/8	59.8±8.20	6.07±4.28

Table 3-3. Demographic characteristics of the participants recruited for the device-assisted upper limb training (n=15).

3.2.6.1 Training protocol

All the participants received self-help upper limb training assisted with the EMG-driven exoneuromusculoskeleton. The training comprised 20 sessions, with the training intensity of 3 – 5 sessions/week, within 7 consecutive weeks. Before the training, a

tutorial session was provided to each participant on the device operation, electrode attachment (the electrode positions were marked on the skin by an experiment operator), wearing skills, and the training protocol. In the first three training sessions, professional assistance was provided in a rehabilitation laboratory at varying levels. The levels of support can be described as follows: (1) the operator supported the participants during the setup and supervised the entire training process in the first session (fully assisted session); (2) the participants mainly completed the session by themselves, with minimum assistance from the operator in the second session (semi-assisted session); and (3) the participants completed the third session independently but with close observation by the operator (independent-with-observation session). Additional semi-assisted sessions were offered to participants who were not ready for the independent-with-observation session; however, no additional semi-assisted session was required by the participants in this study. In the remaining training sessions (i.e., the 4^{th} to 20^{th} sessions), the participants performed the required tasks independently in the laboratory without close supervision of the operator. The operator provided help if required (e.g., if an electrode lead was broken).

In each training session, the participants were seated at a table to maintain a vertical distance of 30-40 cm between the table surface and their shoulder. During the task, the participants' paretic upper limb with the wearable modules was lifted up to 80° vertical abduction of the shoulder with a hanging system (Figure 3-5A). A smartphone was positioned on the table and placed in front of the participant with a horizontal distance of 60 cm. The participants were instructed through a visual indication on the mobile screen to perform device-assisted and repeated limb motions, namely (1) elbow extension, (2) wrist extension with the hand open, (3) wrist flexion with the hand closed,

and (4) elbow flexion, at their natural speed (for totally 90 min in each session). A 15-min break was provided between two consecutive 30-min practice to prevent muscle fatigue. Figure 3-5B shows the training protocol presented with timeline.

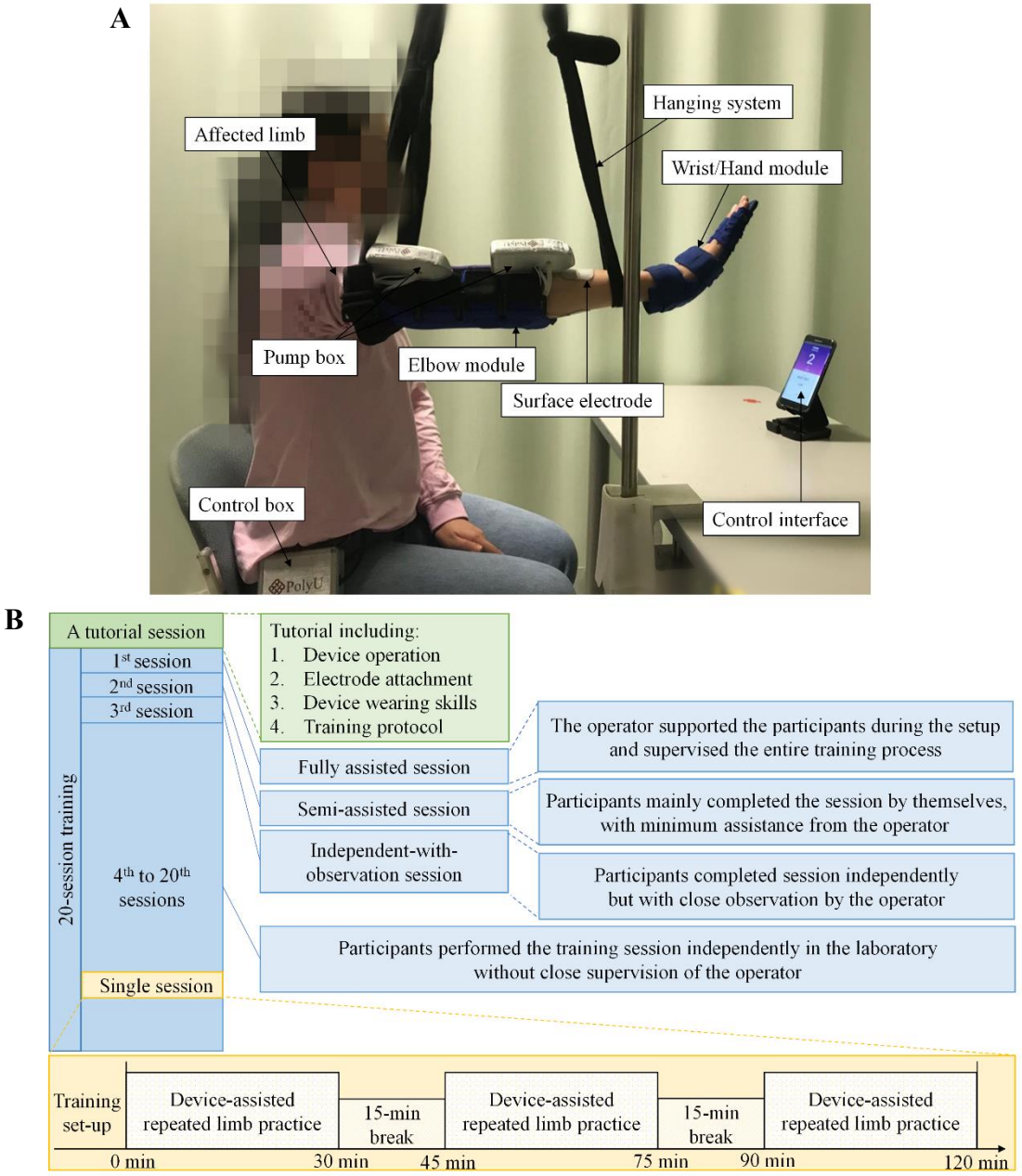

Figure 3-5. (A) Experimental training setup of the EMG-driven exoneuromusculoskeleton in the laboratory, and (B) the training protocol presented with timeline.

3.2.6.2 Evaluation of the training effects

3.2.6.2.1 Clinical assessments

In this study, the training effects were assessed through clinical assessments of the FMA that the full score is 66 for the upper limb assessment and has been sub-scaled into shoulder/elbow (42/66) and wrist/hand (24/66),[80] the Action Research Arm Test (ARAT),[81] the Wolf Motor Function Test (WMFT),[82] the Motor Functional Independence Measure (FIM),[83] and the MAS[77] at the elbow, wrist, and fingers. These clinical assessments were performed thrice in 2 weeks before the training for detection of the baseline stability. The aforementioned clinical assessments were also performed immediately after the last training session and 3 months after the training by a training-blinded assessor.

3.2.6.2.2 Cross-sessional evaluation through EMG

At the beginning of each training session, EMG recordings of the maximum voluntary contractions (MVCs) and a bare arm test (performed in previous studies[75, 107]) were performed. Each participant first received an MVC test[127] for the following target muscle unions or muscles, i.e., the ECU-ED, FCR-FD, TRI, and BIC. While conducting the MVC test on the ECU-ED and FCR-FD, participants were seated at a table and the paretic upper limb was placed on the table with the elbow joint extended to an angle of 130°, and the wrist was held by an experimental operator positioned around its neutral position. The finger positions were set by the operator to obtain an angle around 150° at the MCP joints of the index, middle, ring, and little fingers. During the isometric maximum voluntary extension (IMVE) of the wrist and the four fingers, the ECU-ED

EMG signals were recorded; and during the isometric maximum flexion (IMVF) of the wrist and the four fingers, the FCR-FD EMG signals were captured. During the MVC test on the TRI and BIC, the paretic upper limb was positioned with the shoulder abducted at 70° and the elbow flexed at 90°. During the IMVE and IMVF of the elbow, the TRI and BIC EMG signals were recorded, respectively. The MVC test on each target muscle, or muscle union, was repeated twice and the contraction was maintained for 5 s. The variation of maximum EMG amplitude in the two repetitions was required to be within 10%, otherwise the MVC test would be repeated. The largest EMG amplitude was then selected as the EMG amplitude of MVC for the target muscle union or muscle. A 2-min break was provided between two consecutives contractions to avoid muscle fatigue. The bare arm test comprised horizontal arm reaching, hand grasping, and withdrawing motions, which were similar to the limb practice motions during the training task. The participants were required to use their paretic limbs (without assistance from the system) to repeat the test three times at their natural speed. EMG electrodes (2 × 3 cm^2, Blue Sensor N, Ambu Inc., Ballerup, Denmark) were attached to the skin surface of the aforementioned target muscle unions and muscles (the configuration specified in a previous study[108, 128] was used).The collected EMG signals were amplified with a gain of 1000 (amplifier: INA 333, Texas Instruments Inc., Dallas, TX, USA), band-pass filtered from 10 to 500 Hz, and then sampled with 1000 Hz for digitization for offline processing.[128] Two EMG parameters were calculated for quantitative session-by-session monitoring of the evolution of the muscle activation and coordination patterns: (1) the normalized EMG activation level of each target muscle and (2) the normalized EMG co-contraction index (CI) between muscle pairs. [67, 68] The EMG activation level of a muscle was calculated as follows:

$$\overline{\mathrm{EMG}} = \frac{1}{T}\int_0^T EMG_i(t)dt \qquad (Eq.3)$$

where $\overline{\mathrm{EMG}}$ refers to the average EMG envelope value of muscle *i*, $\mathrm{EMG_i(t)}$ is the EMG envelope signal obtained after normalization with respect to the EMG MVC value of the muscle, and *T* is the length of the signal.

The CI between a pair of muscles can be expressed as follows:

$$\mathrm{CI} = \frac{1}{T}\int_0^T A_{ij}(t)dt \qquad (Eq.4)$$

where $A_{ij}(t)$ is the overlapping activity of EMG linear envelopes for muscles *i* and *j* and *T* is the length of the signal. An increase in the CI value represents increased co-contraction of a muscle pair (broadened overlapping area), and a decrease in the CI value indicates decreased co-contraction of a muscle pair (reduced overlapping area). To obtain the tendency of the EMG parameters of an individual with normalized values (varying from 0 to 1) and to minimize the variations among different participants, a further normalization was applied to the aforementioned EMG parameters of individual participants with respect to the maximal and minimal values of the participants across the 20 training sessions.[107, 128]

3.2.7 Statistics

The normality tests on the ROMs, clinical scores, and EMG data were evaluated using the Lilliefors method with a significance level of 0.05.[84] The ROMs of the wrist and finger joints exhibited significance in the normality test ($P < 0.05$), and the ROMs of the elbow, the clinical score, and the EMG data exhibited nonsignificant probabilities ($P > 0.05$). Kruskal-Wallis one-way analysis of variance (ANOVA) with the Bonferroni post hoc test was used to evaluate the differences in the ROMs of the wrist and finger joints with the four assistance schemes. One-way ANOVA with the Bonferroni post hoc test was used to detect the differences in the ROMs of the elbow with the four assistance

schemes and evaluate the differences in the clinical assessments across different timepoints (three pre-training assessments, a post-training assessment, and a 3-month follow-up assessment) and the EMG parameters (i.e., the normalized EMG activation levels and normalized CIs) across the 20 training sessions. The statistically significant level was set as 0.05 in this study. The significance levels at 0.01 and 0.001 are also indicated.

3.3 Results

3.3.1 Pressure-torque transmission of the musculoskeletons

3.3.3.1 Elbow module

The experimental result for the pressure-torque relationship during the inflation of the elbow musculoskeleton is depicted in Figure 3-6A. A significant linear relationship was found between the pressure and the torque for the elbow musculoskeleton ($P \leq 0.001$, $R^2 = 0.997$). The measured maximum extension torque was 4.3 Nm, which corresponded to an inner pressure of 96 kPa during inflation. Moreover, the torque-to-weight ratio was 27.2 Nm/kg (because the weight of the elbow module was 158 g). The pressure-time relationship for the elbow musculoskeleton is depicted in Figure 3-6B. During inflation, the inner pressure of the elbow musculoskeleton reached ≥96 kPa in <66 s under free loading.

3.3.3.2 Hand module

A significant linear pressure-torque relationship was detected when the

musculoskeleton was used on the MCP joint of the middle finger ($P \leq 0.001$, $R^2 = 0.997$; Figure 3-6C). When the maximal measured inner pressure reached 96 kPa, the corresponding extension torque of the MCP joint of the middle finger was 0.093 Nm. The torque-to-weight ratio was 9.3 Nm/kg, and the total weight of the middle finger was 10 g. The pressure-time relationship for the hand musculoskeleton is depicted in Figure 3-6D. During inflation, the inner pressure of the hand musculoskeleton reached ≥96 kPa within 17 s under free loading.

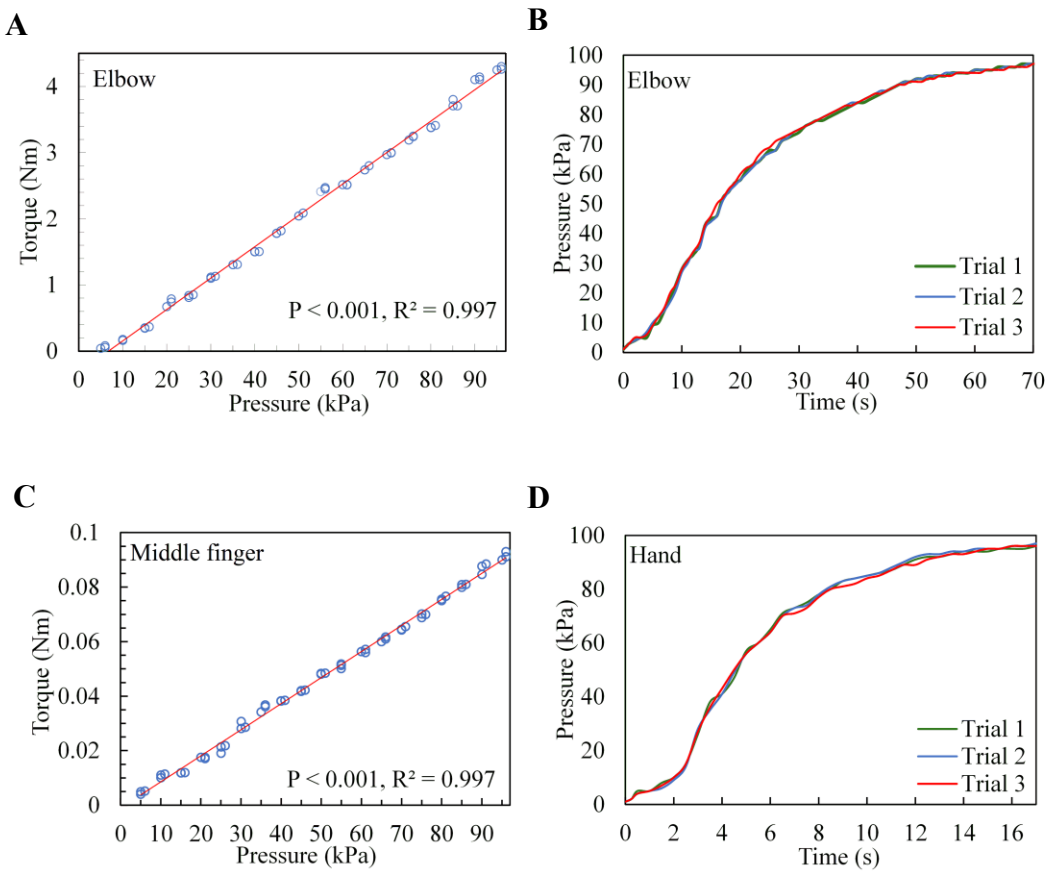

Figure 3-6. (A) Pressure–torque relationship and (B) response time of the inner pressure of the elbow musculoskeleton during inflation with a fully opened valve; (C) pressure–torque relationship of the musculoskeleton for the MCP joint of the middle finger; and (D) response time of the inner pressure of the hand musculoskeleton during inflation

with a fully opened valve.

3.3.2 Evaluation of joint assistance by the EMG-driven exoneuromusculoskeleton

Figure 3-7A and 3-7B depict the ROM variations recorded with different assistance schemes in the evaluation of the elbow and wrist joints, respectively. As shown in Figure 3-7A, the elbow ROM was significantly larger with the assistance from the musculoskeleton (N0M1 and N1M1) than without any assistance from the system (N0M0) ($P = 0.002$, effect size (EF) = 0.123, $F = 5.42$, one-way ANOVA with the Bonferroni post hoc test). With no assistance from the system (N0M0), the elbow ROM achieved its steady state (defined as the ROM value > 95% of the stable value) in approximately 3 s. With only NMES assistance (N1M0) from the system, the elbow ROM reached its steady state in approximately 5 s. With mechanical assistance (N0M1 and N1M1) from the system, both elbow ROM values achieved their steady state in approximately 9 s. As shown in Figure 3-7B, the wrist ROM was significantly larger when the system provided NMES assistance (N1M0 and N1M1) than when the system did not provide NMES support (N0M0 and N0M1) ($P \leq 0.001$, Kruskal-Wallis one-way ANOVA with the Bonferroni post hoc test). With no assistance from the system (N0M0), the wrist ROM achieved its steady state in approximately 2.5 s. With only NMES assistance (N1M0) and only mechanical assistance (N0M1) from the system, the corresponding wrist ROMs achieved their steady state in approximately 4 s. With both NMES and mechanical assistance (N1M1) provided by the system, the wrist ROM achieved its steady state in approximately 6 s. The elbow and wrist ROM values measured in this study (i.e., means and 95% confidence intervals of the related joints

as well as the one-way ANOVA probabilities with the EF or Kruskal-Wallis one-way ANOVA probabilities for the evaluation with respect to the different assistance schemes) are presented in Table 3-4.

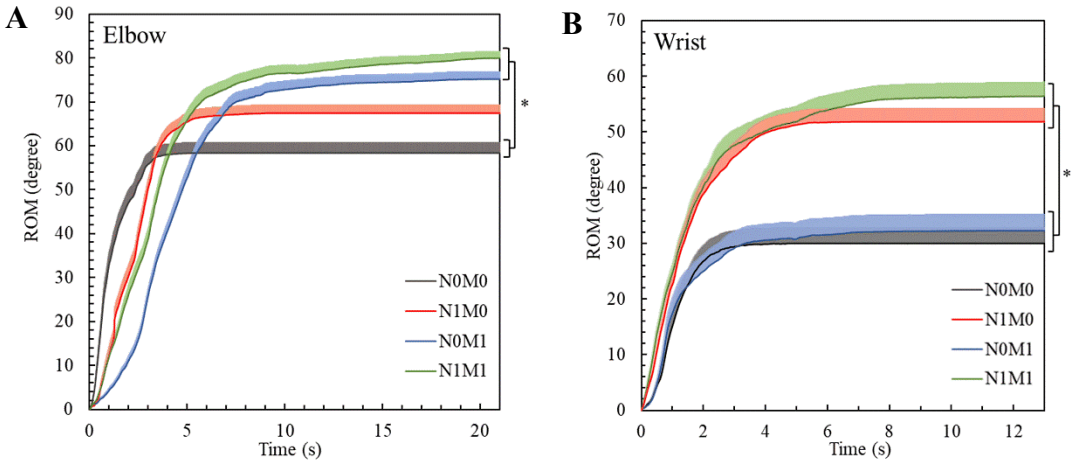

Figure 3-7. Comparison of the dynamic ROM values, which are represented in terms of their means (shaded areas indicate half a standard error (SE)), at the (A) elbow and (B) wrist joints under the different assistance schemes. Significant differences ($P \leq 0.05$) with respect to the assistance scheme are indicated by "*."

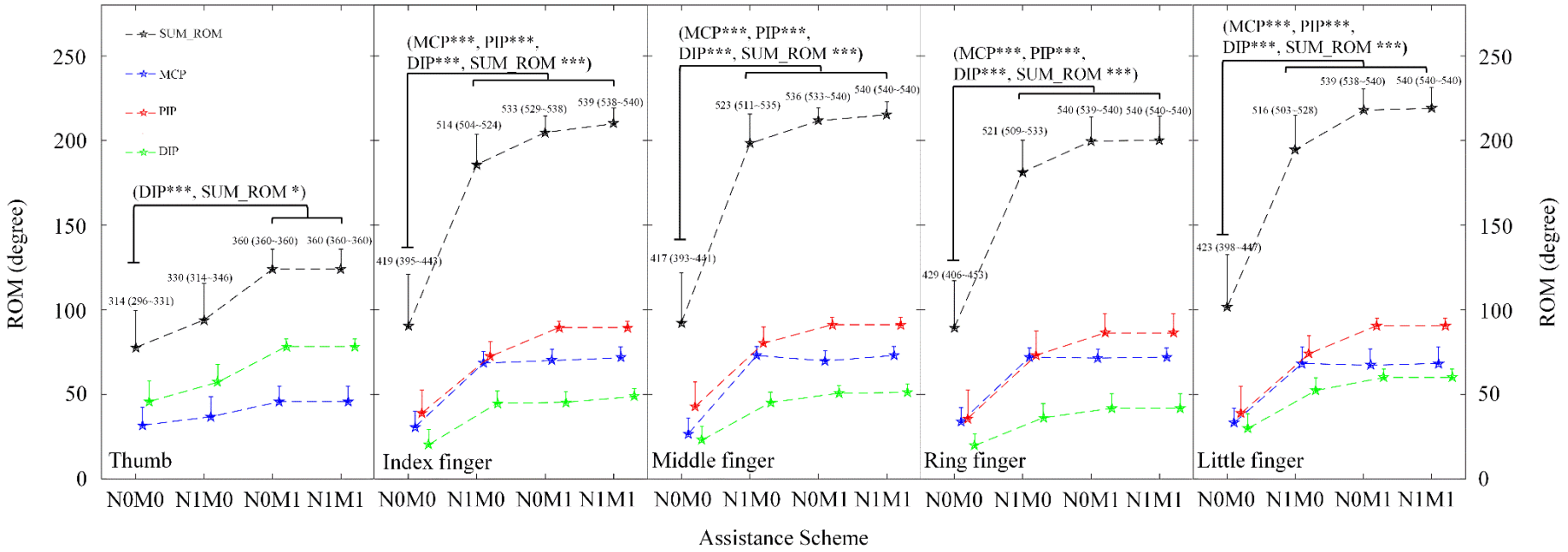
SUM_ROM
MCP
PIP
DIP
(DIP***, SUM_ROM *)
314 (296~331)
330 (314~346)
360 (360~360)
360 (360~360)
Thumb
(MCP***, PIP***, DIP***, SUM_ROM ***)
419 (395~442)
514 (504~524)
533 (529~538)
539 (538~540)
Index finger
(MCP***, PIP***, DIP***, SUM_ROM ***)
417 (393~441)
523 (511~535)
536 (533~540)
540 (540~540)
Middle finger
(MCP***, PIP***, DIP***, SUM_ROM ***)
429 (406~453)
521 (509~533)
540 (539~540)
540 (540~540)
Ring finger
(MCP***, PIP***, DIP***, SUM_ROM ***)
423 (398~447)
516 (503~528)
539 (538~540)
540 (540~540)
Little finger
ROM (degree)
0
50
100
150
200
250
N0M0 N1M0 N0M1 N1M1
Assistance Scheme

Figure 3-8. Comparison of the ROM values of the finger joints, which are represented in terms of their means ± twice the SE (error bar), under different assistance schemes. Significant levels are indicated by * for $P \leq 0.05$, ** for $P \leq 0.01$, and *** for $P \leq 0.001$. The total joint position of each finger is defined as the sum of the final position of each measured joint of the finger after hand opening (indicated with the means and 95% confidence intervals).

Figure 3-8 shows the ROM values recorded with different assistance schemes in the evaluation of the finger joints. The ROM values of the finger joints varied differently with the four assistance schemes. The SUM_ROM value of the thumb ($P \leq 0.01$, Kruskal-Wallis one-way ANOVA with the Bonferroni post hoc test) and the ROM of the DIP joint of the thumb ($P \leq 0.001$, Kruskal-Wallis one-way ANOVA with the Bonferroni post hoc test) were significantly higher when the mechanical assistance provided (N0M1 and N1M1) than when no assistance was provided from the system (N0M0). The SUM_ROM values of the index, middle, ring, and little fingers as well as the ROMs of the MCP, PIP, and DIP joints of the index, middle, ring, and little fingers were significantly higher when the assistance was provided (N1M0, N0M1, and N1M1) than when no assistance was provided (N0M0) ($P \leq 0.001$, Kruskal-Wallis one-way ANOVA with the Bonferroni post hoc test). The ROM values measured in this study for the finger joints (i.e., means and 95% confidence intervals of each joint as well as the Kruskal-Wallis one-way ANOVA probabilities for the evaluation with respect to the different assistance schemes) are listed in Table 3-4.

ROM	N0M0	N1M0	N0M1	N1M1	1-way ANOVA	
	Mean (95% Confidence Interval)				P-value (Partial η^2)	F-value
Elbow joint	58.3 (48.0~68.7)	67.4 (59.2~75.6)	75.2 (67.6~82.7)	80.0 (73.3~86.7)	.002** (.123)	5.42
ROM	**N0M0**	**N1M0**	**N0M1**	**N1M1**	**Kruskal–Wallis 1-way ANOVA**	
	Mean (95% Confidence Interval)				P-value	
Wrist joint	29.9 (17.5~42.4)	51.8 (41.6~62.1)	32.2 (19.5~45.0)	56.4 (45.6~67.3)	.000***	
Thumb						
SUM_ROM	77.7 (55.2~100)	94.0 (71.8~116)	124 (112~136)	124 (112~136)	.008**	
MCP joint	31.8 (21.0~42.6)	36.8 (24.7~49.0)	45.7 (36.2~55.1)	45.7 (36.2~55.1)	.146	
DIP joint	45.8 (33.4~58.2)	57.2 (46.3~68.0)	78.3 (73.8~82.9)	78.3 (73.8~82.9)	.000***	
Index Finger						
SUM_ROM	90.2 (58.7~122)	186 (168~204)	205 (195~215)	210 (201~220)	.000***	
MCP joint	30.8 (21.4~40.2)	68.5 (61.5~75.5)	70.7 (63.2~76.8)	71.7 (65.0~78.3)	.000***	
PIP joint	39.0 (25.0~53.0)	72.5 (63.7~81.3)	89.5 (85.6~93.4)	89.5 (85.6~93.4)	.000***	
DIP joint	20.3 (11.0~29.7)	44.8 (37.5~52.2)	45.3 (38.9~51.7)	48.8 (44.0~53.7)	.000***	
Middle Finger						
SUM_ROM	92.3 (62.2~123)	198 (181~216)	212 (204~220)	215 (208~223)	.000***	
MCP joint	26.7 (17.3~36.1)	73.0 (67.5~78.5)	69.8 (63.8~75.9)	73.0 (67.5~78.5)	.000***	
PIP joint	42.7 (27.8~57.6)	80.2 (70.2~90.1)	91.2 (86.7~95.6)	91.2 (86.7~95.6)	.000***	
DIP joint	23.0 (14.7~31.3)	45.2 (38.8~51.5)	50.7 (45.9~55.4)	51.2 (46.3~56.0)	.000***	
Ring Finger						
SUM_ROM	89.3 (60.8~118)	181 (162~201)	200 (185~214)	200 (186~215)	.000***	
MCP joint	33.7 (25.0~42.3)	72.0 (66.5~77.5)	71.5 (66.1~76.9)	72.0 (66.5~77.5)	.000***	
PIP joint	35.8 (18.7~53.0)	73.2 (58.4~87.9)	86.3 (74.5~98.1)	86.3 (74.5~98.1)	.001***	
DIP joint	19.8 (12.7~26.9)	36.2 (27.4~44.9)	41.8 (32.9~50.8)	41.8 (32.9~50.8)	.001***	
Little Finger						
SUM_ROM	102 (70.1~133)	195 (174~215)	218 (205~231)	219 (206~232)	.000***	
MCP joint	33.2 (24.3~42.0)	68.3 (58.4~78.3)	67.3 (57.5~77.1)	68.3 (58.4~78.3)	.000***	
PIP joint	38.7 (22.3~55.1)	74.0 (63.2~84.8)	90.7 (86.4~95.0)	90.7 (86.4~95.0)	.000***	
DIP joint	29.8 (20.9~38.8)	52.3 (44.6~60.1)	60.0 (55.0~65.0)	60.0 (55.0~65.0)	.000***	

Table 3-4. Means and 95% confidence intervals for each measurement of the elbow, wrist, and fingers joints, as well as the probabilities of the statistical analyses. Differences with statistical significance are denoted using the notation "*". The

significant levels are indicated as * for $P \leq 0.05$, ** for $P \leq 0.01$, and *** for $P \leq 0.001$.

3.3.3 Training effects

All the recruited participants (n = 15) completed self-help upper limb training assisted with the EMG-driven exoneuromusculoskeleton. The participants could wear and take off the developed system, and perform the training tasks independently (i.e., without close supervision and assistance from the operator) in the final 17 training sessions. The most frequently reported problem by the participants was broken leads during wearing and taking off the system, which was solved by on-site soldering or replacing the leads.

3.3.3.1 Clinical assessments

Motor improvements measured by clinical scores (i.e., the FMA, ARAT, and MAS scores) are summarized in Figure 3-9. Significant increases were observed in the FMA full score (Figure 3-9A; $P \leq 0.001$, EF = 0.293, F = 7.27, one-way ANOVA with the Bonferroni post hoc test), FMA shoulder/elbow score (Figure 3-9B; $P \leq 0.001$, EF = 0.222, F = 5.00, one-way ANOVA with the Bonferroni post hoc test), and FMA wrist/hand score (Figure 3-9C; $P \leq 0.001$, EF = 0.386, F = 11.0, one-way ANOVA with the Bonferroni post hoc test) after the training, and these increases were maintained after 3 months. As depicted in Figure 3-9D, the ARAT score significantly increased after the training, and this increase was maintained for 3 months ($P \leq 0.001$, EF = 0.262, F = 6.23, one-way ANOVA with the Bonferroni post hoc test). As shown in Figure 3-9E, the MAS scores at the elbow significantly declined after training, and this decline was maintained for 3 months ($P \leq 0.001$, EF = 0.366, F = 10.1, one-way ANOVA with the Bonferroni post hoc test). Significant decreases were observed in the MAS scores

at the wrist ($P \leq 0.001$, EF = 0.229, F = 5.21, one-way ANOVA with the Bonferroni post hoc test) and fingers ($P \leq 0.001$, EF = 0.391, F = 11.2, one-way ANOVA with the Bonferroni post hoc test) after the training, and these decreases were maintained after 3 months. Table 3-5 lists all the clinical scores measured in this study (i.e., means and 95% confidence intervals of each clinical assessment as well as the one-way ANOVA probabilities with the EF for the evaluation with respect to the assessment sessions).

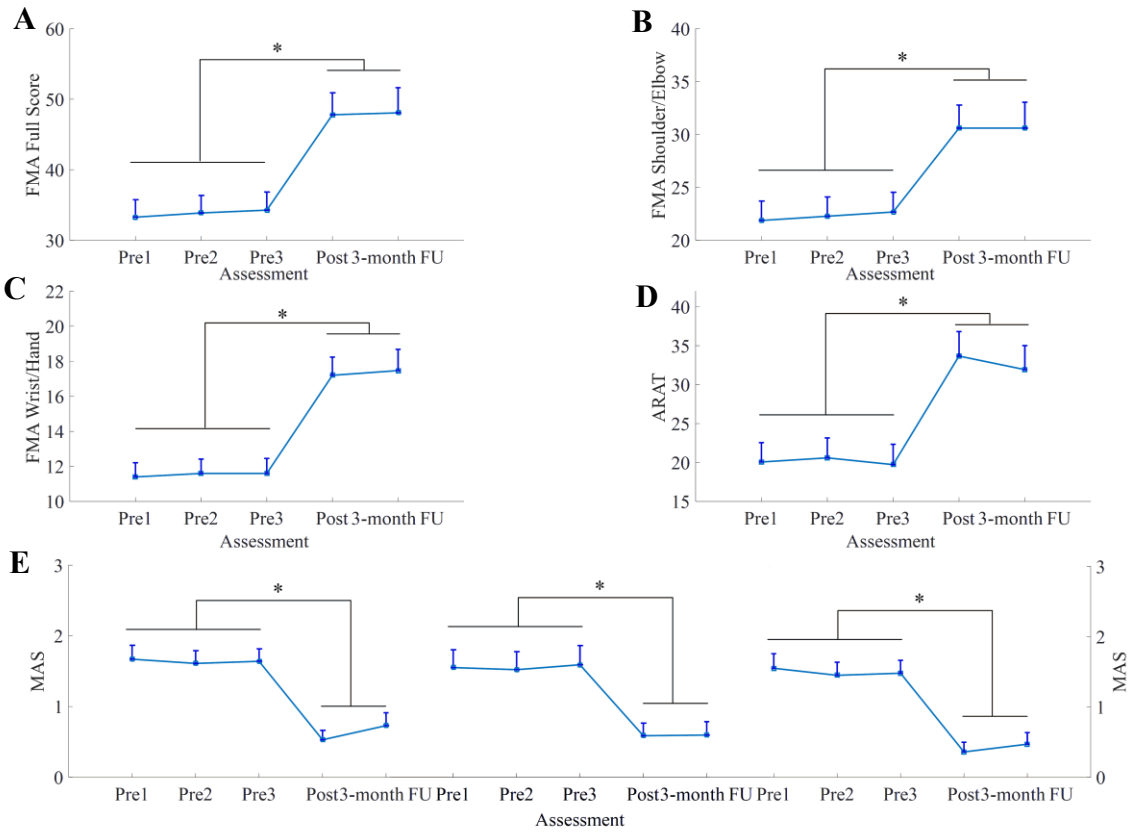

Figure 3-9. Clinical scores measured before, immediately after, and 3 months after the training: (A) FMA Full scores, (B) FMA Shoulder/Elbow scores, (C) FMA Wrist/Hand scores, (D) ARAT scores, and (E) MAS scores at the elbow, wrist, and fingers. The clinical scores are presented as means ± twice the SE (error bar) in each evaluation session. The significant difference is indicated by "*" ($P \leq 0.05$).

3.3.3.2 EMG parameters

Figure 3-10 presents the EMG parameters (i.e., the normalized EMG activation level and normalized CI), which exhibited significant variations in the evaluations across the 20 training sessions. A significant decrease in the EMG activation level was observed for the FCR-FD muscle union (Figure 3-10A; $P \leq 0.001$, EF = 0.168, F = 2.98, one-way ANOVA with the Bonferroni post hoc test) and BIC muscle (Figure 3-10A; $P \leq 0.001$, EF = 0.138, F = 2.36, one-way ANOVA with the Bonferroni post hoc test). Figure 3-10B illustrates the significant decreases in the CI values between the FCR-FD and ECU-ED muscle unions (P = 0.009, EF = 0.119, F = 2.00, one-way ANOVA with the Bonferroni post hoc test), the ECU-ED muscle union and the BIC muscle (P = 0.002, EF = 0.108, F = 1.78, one-way ANOVA with the Bonferroni post hoc test), the FCR-FD muscle union and the BIC muscle ($P \leq 0.001$, EF = 0.168, F = 2.97, one-way ANOVA with the Bonferroni post hoc test), and the BIC and TRI muscle pair ($P \leq 0.001$, EF = 0.139, F = 2.38, one-way ANOVA with the Bonferroni post hoc test) during the evaluations across the 20 training sessions. No significant increase or decrease was detected in the EMG parameters of other target muscles and muscle pairs.

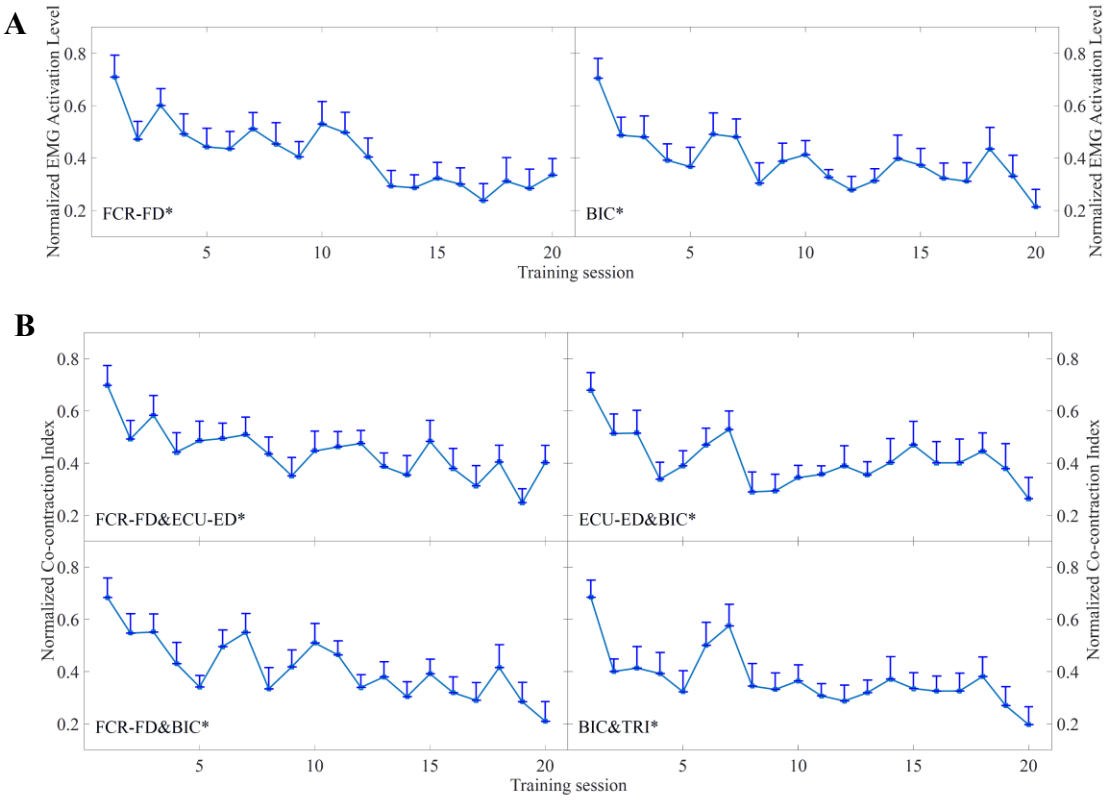

Figure 3-10. Variations in the EMG parameters recorded across the 20 training sessions: (A) the normalized EMG activation levels of the FCR–FD muscle union and BIC muscles during the bare hand evaluations and (B) the changes in the normalized CIs between the FCR–FD and ECU–ED muscle unions, the ECU–ED muscle union and the BIC muscles, the FCR–FD muscle union and BIC muscles, and the BIC and TRI muscle pair during the bare hand evaluations. The EMG parameter values are presented as means ± twice the SE (error bar) for each session. The significant difference is indicated by "*" ($P \leq 0.05$).

Evaluation	Pre 1	Pre 2	Pre 3	Post	3-Month Follow-up	1-way ANOVA	
	Mean (95% Confidence Interval)					P-value (Partial η^2)	F-value
FMA							
Full Score	33.3 (28.0~38.6)	33.9 (28.5~39.2)	34.3 (28.8~39.8)	47.8 (41.2~54.5)	48.1 (40.4~55.7)	.000*** (.293)	7.27
Wrist/Hand	11.4 (9.66~13.1)	11.6 (9.85~13.4)	11.6 (9.77~13.4)	17.2 (15.0~19.4)	17.5 (14.9~20.1)	.000*** (.386)	11.0
Shoulder/Elbow	21.9 (17.9~25.8)	22.3 (18.4~26.2)	22.7 (18.7~26.7)	30.6 (25.9~35.3)	30.6 (25.4~35.9)	.001*** (.222)	5.00
ARAT	20.1 (14.7~25.4)	20.6 (15.1~26.1)	19.7 (14.1~25.4)	33.7 (26.9~40.4)	31.9 (25.3~38.6)	.000*** (.262)	6.23
WMFT							
Score	44.5 (36.3~52.7)	43.7 (35.4~51.9)	44.9 (36.5~53.2)	55.1 (47.8~62.5)	52.7 (44.3~61.2)	.159 (.088)	1.71
Time	38.8 (25.2~52.5)	40.1 (26.8~53.4)	40.6 (26.6~54.5)	24.2 (14.4~34.0)	28.0 (16.4~39.7)	.107 (.101)	1.98
FIM	66.0 (65.6~66.4)	66.0 (65.6~66.4)	66.0 (65.6~66.4)	66.1 (65.7~66.5)	66.1 (65.7~66.5)	.954 (.009)	0.167
MAS							
Elbow	1.67 (1.24~2.09)	1.61 (1.23~2.00)	1.64 (1.26~2.02)	0.53 (0.25~0.82)	0.73 (0.34~1.12)	.000*** (.366)	10.1
Wrist	1.56 (1.02~2.10)	1.53 (0.98~2.08)	1.60 (1.02~2.18)	0.59 (0.20~0.97)	0.60 (0.19~1.01)	.001*** (.229)	5.2
Finger	1.55 (1.10~1.99)	1.45 (1.06~1.85)	1.48 (1.09~1.87)	0.36 (0.06~0.66)	0.47 (0.11~0.82)	.000*** (.390)	11.2

Table 3-5. Means and 95% confidence intervals for each measurement in the clinical assessments, as well as the probabilities and estimated effect sizes of the statistical analyses. Differences with statistical significance are denoted by the notation "*". Significant levels are indicated as* for $P \leq 0.05$, ** for $P \leq 0.01$, and *** for $P \leq 0.001$.

3.4 Discussion

The EMG-driven exoneuromusculoskeleton was developed to assist self-help poststroke upper limb training with minimal professional assistance. The pressure-torque transmission properties of the designed musculoskeleton were evaluated, and the assistive capability of the exoneuromusculoskeleton on patients with chronic stroke was assessed using different assistance combinations of NMES and the musculoskeleton. A pilot trial was also conducted to validate the feasibility of device-assisted self-help upper limb rehabilitation.

3.4.1 Design of exoneuromusculoskeleton

In this study, we integrated soft pneumatic muscles, exoskeleton extension, and NMES in the design of the exoneuromusculoskeleton to assist the upper limb physical practice at the elbow, wrist, and fingers for patients with chronic stroke. The mechanical support with NMES to the main extensor of a joint was applied in joint extension because upper extremity (UE) extension is more difficult than flexion for most patients after stroke because of the muscle weakness in their affected UE extensors and muscle spasticity in their UE flexors,[112] which lead to increased resistance in the extension ROM.[129, 130] The results indicated that the elbow musculoskeleton exerted an extension torque of up to 4.3 Nm across the elbow joint when the maximum inner pressure of the musculoskeleton reached 96 kPa (Figure 3-6A), which was larger than the reported joint resistance in stroke patients with MAS scores of ≤3 at the elbow.[131] The hand musculoskeleton could generate a maximal extension torque of 0.093 Nm across the MCP joint of the middle finger when its maximum inner pressure reached 96 kPa

(Figure 3-6C), which was similar to the reported finger resistance in stroke patients with MAS score of ≤3 at the fingers.[132] The musculoskeletons alone could enable the recruited stroke patients with severe-to-moderate upper limb impairments (i.e., 15 < FMA < 45) to perform extension at the related joints. It was manifested by evaluating the assistive capability of the system on patients with chronic stroke. The results showed that the ROM values for the elbow and finger joints were significantly higher when using the N0M1 assistance scheme (i.e., the joints assisted by the musculoskeletons only) than when not providing any assistance (N0M0) during joint extension. Spasticity was defined as motor disorder characterized by a velocity-dependent increase in tonic stretch reflexes with exaggerated tendon jerks, resulting from hyperexcitability of the stretch reflex, as one component of the upper motor neuron syndrome.[112] It was reported that excessive reflex torque would be exerted when the joint rotation velocity was high, e.g., larger than 90°/s in stroke patients with MAS scores of ≤3 at the joint.[117, 133] With the assistance from both the musculoskeleton and the NMES (N1M1), the elbow joint extended with an average angular velocity from 8° to 15°/s (Figure 3-7A). In this study, the spasticity at the elbow, the wrist and the fingers of the recruited subjects were ≤3 as measured by the MAS, and the angular velocities at the joints were all below 15°/s in the device-assisted motions. Hence, no excessive resistance due to spasticity was generated during the evaluation and training.

In the developed system, the musculoskeletons were attached to the ventral side of the joints and provided torque output to the related joints through inflation. This design is different from most current exoskeletons or soft robotic equipment for UE rehabilitation, in which mechanical assistance is provided from the dorsal side of a joint.[59] Larger assistive torques are required when providing assistance from the dorsal side of a joint than when providing assistance from its ventral side.[134, 135] Less torque output is also

associated with a lower power consumption and more compact size.

The torque-to-weight ratios of the musculoskeleton were 27.2 Nm/kg for the elbow and 9.3 Nm/kg for the fingers. These ratios were comparable to those (7.7-28.3 Nm/kg) reported for other pneumatic soft robots in the literature[105, 134, 136] and considerably higher than those of rigid exoskeletons. For example, MyoPro (elbow–wrist–hand exoskeleton), its elbow-hand module was reported to have a maximal torque-to-weight ratio of 7 Nm/kg for the elbow and 3.4 Nm/kg for the fingers as well as a total weight of approximately 1.8 kg.[137] In previous studies, pneumatic soft robots were actuated with powerful and heavy compressors, whose weights were not counted in the calculation of the torque-to-weight ratio.[134-136, 138] The miniature compressors used in the developed exoneuroneuromusculoskeleton were the wearable parts of the system. Thus, the total weight on the upper limb was 368 g when the system was fully mounted (Figure 3-1). The developed system with a lightweight and wearable design has potential to support mobile rehabilitation for the upper limb.

In the free loading test, the inner pressure of the elbow musculoskeleton reached close to 100 kPa in <66 s (Figure 3-6B) and that of the hand musculoskeleton reached nearly 100 kPa within 17 s (Figure 3-6D). The air volume of the pneumatic chamber of the actuator was reduced by the musculoskeleton with mechanical integration of the rigid exoskeleton and pneumatic muscle. Thus, a fast response time was obtained for inflation with the miniature compressors. More powerful and larger compressors were used in soft pneumatic robots in previous studies[134-136, 138] to achieve equivalent mechanical outputs and responses to assist upper limb movements.

In the extension phase, the biological muscle actuation induced by NMES generated

additional force for limb extension, which reduced the demand for the external force produced by the musculoskeleton. In this study, wrist extension was only supported by NMES to minimize the size of the mechanical structure of the system. One-channel NMES can support wrist extension with the hand open in clinical practice,[18] and positive rehabilitation outcomes were observed in a previous study in wrist/hand practice assisted by mechanical support and one-channel NMES of the ECU-ED muscle union.[74] The assistive capability of the exoneuromusculoskeleton for patients with chronic stroke was also evaluated with different assistance combinations of NMES and the musculoskeleton. The results of the evaluations are discussed in the following section.

3.4.2 Evaluation of joint assistance by the EMG-driven exoneuromusculoskeleton

Most stroke survivors have a limited ability to perform voluntary joint extension.[139, 140] It is difficult to achieve the ROMs of able-bodied people due to the spasticity at the flexors,[141] muscle discoordination of the UE flexors and extensors during extension motion,[129, 142] and weakness at the extensors.[143] Thus, assisting joint extension to achieve increased ROMs is necessary in poststroke rehabilitation.[124]

In this study, the assistive capability of the EMG-driven exoneuromusculoskeleton for the elbow, wrist, and finger joints was evaluated according to the ROMs achieved for the related joints in the extension phase with different assistance schemes. The assistive performance was evaluated on participants with chronic stroke having severe-to-moderate upper limb impairments. All participants recruited in this work could

complete the elbow flexion from 170° to 30° with their residual voluntary effort, together with NMES assistance. Wrist flexion with the hand closed could be achieved through the NMES on the FCR-FD muscle union, together with the residual voluntary effort from the flexors of the wrist and fingers. In the evaluation, all participants could flex their related joints through their own voluntary effort to their initiated position after the extension of the joints.

In the elbow session, the ROM of the elbow joint was significantly higher with mechanical assistance (N0M1 and N1M1) from the system than without assistance (N0M0). This result implied that the elbow ROM was sensitive to the mechanical assistance from the musculoskeleton. Figure 3-7A indicates that a longer time was required to reach the steady states of the elbow ROMs with mechanical assistance (N0M1 and N1M1) to the elbow than without mechanical assistance (N0M0 and N1M0). It could be related to the interaction between the participants' voluntary motion and the mechanical support from the musculoskeleton (i.e., the pressure-torque transmission rate of the musculoskeleton, Figure 3-6B). However, it was also observed that with both NMES and mechanical assistance (N1M1), the elbow ROM values reached their steady state in approximately 9 s with an average of joint angle of 166° (at the 9^{th} s), which was considerably shorter than the time required for achieving the full extension of the elbow musculoskeleton with an inner pressure of 96 kPa (i.e., 66 s) under free loading (Figure 3-6B). The response time in elbow extension was shortened mainly because of a decreased inner pressure requirement for the elbow musculoskeleton during inflation when the residual voluntary muscle effort exerted from the participants together with the assistance from NMES to the TRI muscle, when applied the system to the participants. It was also observed that when only mechanical

assistance was provided (N0M1), the elbow ROM values reached their steady state in approximately 9 s with a relatively smaller joint angle of the elbow compared to that of N1M1 (Figure 3-7A). This result implied that the NMES assistance could cause additional extension at the elbow.

In the wrist session, the wrist ROM was significantly larger when providing NMES assistance (N1M0 and N1M1) for the wrist extension than when not providing NMES assistance (N0M1and N0M0). This result implied that NMES assistance considerably influenced the achievement of significantly larger ROM at the wrist. It is because the wrist movement was only supported by NMES in the designed system. With NMES assistance at the ECU-ED muscle union and mechanical assistance at the fingers (N1M1), the wrist ROM values reached their steady state in approximately 6 s with the average angle of wrist extension of 54° (at the 6^{th} s), and the wrist angle finally reached a mean of 56° at 13^{th} s (Figure 3-7B). The wrist ROM with both NMES on ECU-ED and the mechanical assistance at the fingers (N1M1) was larger than that with NMES on ECU-ED only (N1M0) (Figure 3-7B). The aforementioned results indicated that the mechanical assistance at the fingers could lead to an increased wrist ROM, which was consistent with the finding of a previous study on wrist mobility. The aforementioned study on wrist mobility suggested that the wrist extension angle was lower when the hand was in a closed-fist position than when the fingers were unconstrained.[125]

In the finger session, the ROMs of the MCP and DIP joints of the thumb were significantly larger with mechanical assistance (N0M1 and N1M1) than with no assistance (N0M0) (Figure 3-8). This result indicated that the ROM of the thumb was mainly facilitated by the mechanical torque (N0M1 and N1M1). Figure 3-8 indicates

that the ROMs of the MCP, PIP, and DIP joints of the index, middle, ring, and little finger were significantly larger with mechanical assistance (N1M0, N0M1, and N1M1) than with no assistance (N0M0). The largest finger ROM was achieved when the fingers received both NMES and mechanical assistance (N1M1) (Figure 3-8). The maximal finger ROMs were reached within 12 s, which was shorter than the time required time for reaching an inner pressure of 96 kPa (i.e., 17 s) under free loading (Figure 3-6D). The shortened response time was mainly because of the residual voluntary effort exerted from the finger extensors together with the assistance from NMES to the ECU-ED muscle union.

The results (Table 3-4) indicated that the participants with severe-to-moderate upper limb impairments could perform limb movements with significantly larger ROMs at the elbow, wrist, and fingers when their affected upper limb assisted with both NMES and mechanical assistance (N1M1) from the developed system than when using their voluntary effort only (N0M0). This finding was consistent with that in our previous study on the use of a hybrid system of exoskeleton and NMES for poststroke upper limb rehabilitation,[74, 144] where the best limb performance was obtained when both mechanical and NMES assistances were provided.

3.4.3 Self-help upper limb training assisted by the EMG-driven exoneuromusculoskeleton

The feasibility of the proposed self-help rehabilitation training was evaluated, and all the participants completed the training with minimal professional assistance in the laboratory. Close professional assistance was provided only in the first three training

sessions. All the participants completed the remaining 17 training sessions independently, and they achieved significant motor improvements in the upper limb after the training. The results obtained in the evaluation sessions indicated that the participants could achieve the largest ROMs with the N1M1 assistance scheme. Therefore, the N1M1 scheme was adopted in the pilot trial. Together with the residual voluntary effort from the paretic limb, the time needed for a cycle of the training task, namely (1) elbow extension, (2) wrist extension with the hand open, (3) wrist flexion with the hand closed, and (4) elbow flexion, was from 40 to 50 s, which was comparable to their natural speed in the paretic upper limb.[74] With the N1M1, the time needed for performing elbow extension was approximately 15 s, wrist extension with the hand open was around 12 s, wrist flexion with the hand closed was approximately 6 s, and elbow flexion was around 8 s. It was observed that performing flexions of the related joints were easier and faster than the extensions, since most of the stroke survivors had superior voluntary motion capability in performing joint flexion than extension.[112]

The training improved voluntary motor functions of the entire paretic upper limb and released the muscle spasticity at the elbow, wrist, and fingers. The voluntary motor function recovery of the related joints of the entire paretic upper limb was indicated by the significant increase in the FMA (shoulder/elbow and wrist/hand) scores after the training. These motor function improvements were maintained at 3-month follow-up. A significant increase was also found in the ARAT scores after the training. This finding not only suggested improved voluntary motor functions of the upper limb but also indicated the recovery of finger function, including grasping, gripping, and pinching movements with fine precision control of the fingers. Stroke survivors usually exhibit muscle discoordination due to muscle spasticity and compensatory motions in the

affected limb.[29] The release of flexor spasticity in the elbow, wrist, and fingers was found after the training, as revealed by the significant decrease in the MAS scores at the related joints after the training. The decrease in the MAS scores after the training also suggested improved muscle coordination and control of synergic muscle activity in proximal and distal joints.[71] With NMES assistance for the extensors, the muscle spasticity at the elbow, wrist, and fingers was effectively reduced. This finding was consistent with those of clinical trials on NMES-assisted poststroke rehabilitation.[107, 108, 144]

Limb practice with close-to-normal muscular coordination and minimized compensatory motions was achieved through the combined assistance of NMES and mechanical torque in the joint extension phases.[74, 107] Such limb practice led to a reduction in excessive muscle activities and superior muscle coordination, as revealed by the decrease in the EMG activation levels at the flexors, co-contractions between the antagonist muscle pairs related to the wrist/hand and elbow, and co-contraction between the elbow flexor and the distal joints. The significant decrease in the EMG activation levels of the FCR-FD muscle union and BIC muscle indicated a reduction in excessive muscle activities of the related muscles during the arm reaching and withdrawing as well as the hand opening and grasping motions, which suggested that the muscle spasticity of the related joints was reduced (manifested in the significantly decreased MAS scores at the elbow, wrist, and fingers after training). The CIs revealed the recovery of muscular coordination and the muscular co-activity within a joint or across joints in the upper limb.[67, 68] The significant decreases in the CIs of the FCR-FD and ECU-ED muscle unions and the BIC and TRI muscle pair indicated that the muscle coordination for achieving the reaching and withdrawing motions through the flexion

and extension at the elbow, wrist, and finger joints were improved after training. Various compensatory movements from the proximal joints were observed during motions at the distal joints for patients with stroke.[18, 62] These compensatory movements can result in excessive co-contractions in the muscles related to the proximal and distal joints. The significantly decreased CIs between the ECU-ED muscle union and BIC muscle and between the FCR-FD muscle union and BIC muscle indicated a reduction in the co-activities between cross-joint muscles during limb motions, improvements in isolation of the wrist and finger movements from the elbow movements. It implied that compensation movements from co-contraction on the proximal joint during distal joint motions were reduced. Conclusive EMG results were found in (1) the proximal and distal flexors, i.e., significant decreased in the EMG activation level for the BIC and FCR-FD, (2) the proximal and distal antagonist muscle pairs, i.e., significant decreased in the CI values between the BIC and TRI, and the FCR-FD and ECU-ED, and (3) cross joint muscles, i.e., significant decreased in the CI values between the ECU-ED and BIC, and the FCR-FD and BIC. These results indicated a reduction in excessive muscle activities in the flexors, mainly related to the release of spasticity, and a reduction in co-contraction between a muscle pair. The nonsignificant EMG parameters were mainly related to the ECU-ED and TRI, which could be related to the weakness in these extensors,[112, 143] or a small sample size in this work. In our future work, large scale randomized controlled trials will be conducted.

It was understood that the treatment with NMES could induce fatigue in a muscle due to the reversed recruiting sequence of muscle fibers in comparison with that during voluntary muscle contractions.[32] Mean frequency drop in EMG was used for monitoring the process of muscle fatigue.[145] We compared the mean frequencies of the EMG signals of the driving muscles in a session, i.e., EMG signals used for the

triggering control. The average mean frequency variation in a session was <5%, which could be considered as the muscles were not fatigued in the training.[146] Furthermore, a 15-min break was provided between two consecutive 30-min practice to prevent muscle fatigue. NMES induced possible muscle fatigue was minimized during the training of this study.

After the EMG-driven exoneuromusculoskeleton assisted self-help upper limb training, all the participants exhibited improved motor functions, reduced muscle spasticity, and superior muscle coordination associated with significantly improved clinical scores and cross-session-recorded EMG parameters. These results suggested that coordinated multi-joint limb practice with the designed assistive function of NMES and the musculoskeleton can facilitate effective motor recovery of stroke patients with severe-to-moderate upper limb impairments.

3.5 Periodic Summary

In this study, a novel EMG-driven exoneuromusculoskeleton was designed for supporting self-help poststroke upper limb rehabilitation with minimum professional assistance. The developed system could assist intensive and repeated upper limb practice at the elbow, wrist, and fingers under the voluntary intention control by residual voluntary EMG signals from the affected upper limb, with a lightweight, compact and low-power-requirement design. The results indicated that the largest ROMs were achieved when the related joints were provided both NMES and mechanical assistance. The participants (patients with chronic stroke) could complete the self-help device-assisted training with minimal professional assistance (i.e., assistance on the training setup and device operation was provided only in the first three training sessions). When adopting the optimal NMES and robot assistance scheme, the EMG-driven exoneuromusculoskeleton assisted rehabilitation program could facilitate motor improvement in the affected upper limb of the participants with chronic stroke. After 20-session device-assisted training, significant motor improvements were achieved, including improved voluntary motor functions in the entire upper limb; released muscle spasticity at the elbow, wrist, and fingers; and improved muscular coordination in the entire upper limb.

CHAPTER 4

HOME-BASED SELF-HELP TELEREHABILITATION OF THE UPPER LIMB ASSISTED BY AN ELECTROMYOGRAPHY-DRIVEN WRIST/HAND EXONEUROMUSCULOSKELETON AFTER STROKE

4.1 Introduction

Most patients with stroke who are discharged home from inpatient poststroke rehabilitation have residual motor impairment of the upper limb, especially in the distal joints (i.e., the wrist and the fingers), which greatly inhibits their ability to perform activities of daily living (ADLs).[17, 43] Although the traditional viewpoint on poststroke rehabilitation suggested that significant motor recovery mainly occurs in the first 6 months after the onset of a stroke (i.e., acute and subacute periods),[22] more recent studies have indicated that significant motor improvements could also be achieved in

the chronic period after stroke through physical training as long as such training is as intensive as the one provided to inpatients.[23, 24] Continuous and regular physical therapy is required to improve the wrist/hand function of outpatients with chronic stroke.[147] The restoration of limb function after stroke depends on intensive and repetitive training of the paralyzed limb[25, 26] with maximized voluntary motor effort[27, 28] and minimized compensatory motions in close-to-normal muscular coordination.[28, 29] However, the provision of effective wrist/hand rehabilitation services for outpatients with chronic stroke is insufficient in the current healthcare system in the world.

In most cases, outpatients have limited access to wrist/hand treatments with the necessary training intensity[148, 149] because of resource constraints due to factors such as an expanding stroke population and a lack of professionals worldwide,[13, 63] as well as other difficulties such as commuting[17] to the outpatient services in day hospitals, and the restriction of social distancing during the COVID-19 pandemic. Home-based telerehabilitation with minimum assistance and remote supervision by professionals (i.e., self-help operation) is a promising approach for sustaining of physical treatment after discharge and enhancing the accessibility of rehabilitation resources to improve the wrist/hand motor functions of discharged patients.[150-152]

However, few studies have focused on techniques for effective self-help upper limb rehabilitation, especially for distal joints.[150] Currently, most studies on home-based telerehabilitation have been based on virtual reality (VR) techniques because home-based VR training is more convenient for and accessible to outpatients than conventional therapy in a clinic or day hospital.[150, 153] Nevertheless, those systems focus on assessment or monitoring of limb performance rather than providing the necessary

physical assistance for the patients to achieve the desired movements.[150, 154-158] Rehabilitation robots have been developed to provide mechanical assistance that mimics physical support from a therapist in conventional therapy; these robots can alleviate the labor-intensive aspects of hands-on physical therapy by performing repetitive therapeutic tasks intensively under the supervision of a therapis,[13] and these robotic therapies for distal joints have been reported to be effective for improving upper limb motor function[42, 43]. However, the majority of the existing rehabilitation robots are heavy, have complex mechanical designs, and require large power supplies, large physical spaces in conventional environments (e.g., clinic), and close professional supervision, which are significant deterrents to their use by patients independently at home.[13, 159]

Furthermore, using robot alone has a limitation in directly activating the desired muscle groups because the target muscles of patients with stroke usually cooperate with compensatory motions from other muscular activities.[70] Compensatory motions from the trunk and the proximal joints, i.e., abnormal motor synergies, are commonly observed in most persons with chronic stroke when they attempt to reach an object or orient their hand to grasp an object.[18] While neuromuscular electrical stimulation (NMES) combined with robotic therapy, the robotic assistance could provide sensorimotor experiences with precise kinematics to realize the desired movements,[160] and NMES could activate the target muscles and reduce compensation from alternative muscle synergies.[36] Thus, the combined NMES-robot treatment has been suggested to facilitate close-to-normal muscular coordination with reduced compensation motions, and it has yielded more effective rehabilitation outcomes than upper limb rehabilitation treatments that use only NMES or only robots.[34] Electromyography (EMG) of the

paralyzed limb to indicate voluntary intention to integrate voluntary motor effort during practice has been recommended for optimizing therapeutic outcomes.[46] EMG-driven training systems have yielded superior improvements in motor functions with longer sustainability than those with passive limb motions,[47] especially for voluntary motor control of the upper limb. Therefore, EMG-driven NMES-robot therapy for home-based self-help training is desirable for effective wrist/hand rehabilitation for outpatients with chronic stroke.

A novel EMG-driven exoneuromusculoskeleton (ENMS) for self-help upper limb rehabilitation after stroke was developed recently by our team.[161, 162] Taking the advantages of exoskeleton, pneumatic muscle, and NMES, the developed system is lightweight, compact, and has low power consumption. The system can assist the extension and flexion of the elbow, wrist, and finger joints under voluntary effort control through EMG. The system consists of an elbow module and a wrist/hand module that can work collectively or separately. The wrist/hand module can work independently as an EMG-driven wrist/hand ENMS (WH-ENMS) to assist wrist/hand movements during training. The rehabilitation effects of the EMG-driven ENMS have been investigated in 15 participants with chronic stroke, followed by a 20-session training program in a neurorehabilitation laboratory, where the participants completed the training independently with the system after they received a tutorial session and three guided training sessions (including practicing device operation and training setup). The participants exhibited significant improvements in voluntary motor control and muscle coordination of the paretic limb after the EMG-driven ENMS-assisted upper limb training. No safety problems were reported by either the experiment operators or the participants throughout the study period. The system offers the possibility of home-

based self-help wrist/hand training for discharged patients with chronic stroke. However, the feasibility of using the EMG-driven WH-ENMS for self-help upper limb training and its rehabilitation effects in a home setting had not been investigated.

Therefore, in this study, we aimed to determine the feasibility of home-based self-help training assisted by the EMG-driven WH-ENMS on outpatients with chronic stroke and investigate its rehabilitation effects. Our hypothesis was that the participants who received the home-based self-help telerehabilitation training assisted by the EMG-driven WH-ENMS would obtain motor improvements in the distal joints, better muscle coordination of the paretic upper limb, and reduce compensatory movements when performing limb tasks.

4.2 Methods

A single-group trial was conducted on discharged patients with chronic stroke (n = 11) who underwent a home-based self-help telerehabilitation program consisting of 20 sessions of wrist/hand training assisted by the EMG-driven WH-ENMS. The training outcomes were evaluated through clinical assessments, EMG evaluations and kinematic analysis.

4.2.1 EMG-driven WH-ENMS

The EMG-driven WH-ENMS used in this study is shown in Figure 4-1A. The system can be worn on the paretic upper limb and assist a stroke survivor in performing phasic wrist/hand coordinated movements, namely (1) wrist extension with the hand open and (2) wrist flexion with the hand close.

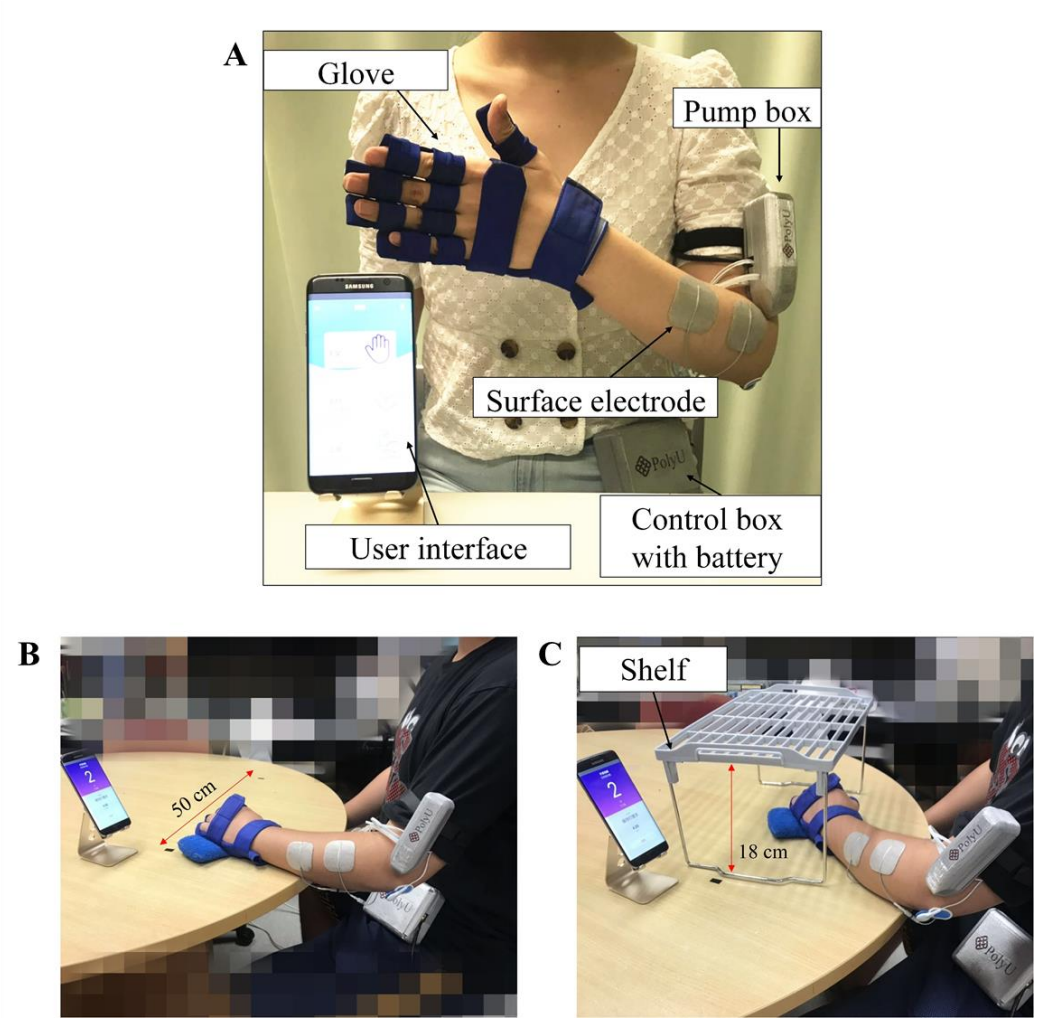

Figure 4-1. Experimental and training set up of the EMG-driven WH-ENMS. (A) Photograph of the EMG-driven WH-ENMS. The training set up in a session assisted by the EMG-driven WH-ENMS and configuration of (B) the horizontal task and (C) vertical task.

The system consists of a wearable glove with a textile bracing on the hand, a pump box mounted on the upper arm and a control box carried on the waist. A rechargeable 12-V Li-ion battery inside the control box can support continuous system usage for 4 hours. The wearable glove with the embedded musculoskeletal hand comprises five pneumatic finger muscles and a three-dimensional printed exoskeletal connector fixed on the palm

side. The pneumatic muscles can provide extension torque to individual digits during inflation, and it deflated when the valve is opened. Each pneumatic muscle can generate a maximal extension torque of 0.1 Nm across the MCP joint of a finger when its inner pressure reaches 96 kPa [162]. Two-channel NMES was applied to the wrist/finger extensors (i.e., the extensor carpi ulnaris (ECU) and the extensor digitorum (ED)) and flexors (i.e., the flexor carpi radialis (FCR) and the flexor digitorum (FD)) to assist wrist/finger extension and flexion, respectively, through two pairs of reusable surface electrodes (5 × 5 cm^2, PALS Neurostimulation Electrodes, Axelgaard Manufacturing Co., Ltd., Fallbrook, CA, USA). The muscles of the ECU and ED and the muscles of the FCR and FD were treated as an ECU-ED muscle union and a FCR -FD muscle union, respectively, for both NMES and EMG detection in this study due to the close anatomical proximity between the FCR and FD muscles and between the ECU and ED muscles.[108] The NMES outputs were square pulses with a constant amplitude of 70 V, stimulation frequency of 40 Hz, and a manually adjustable pulse width in the range of 0-300 μs (with a threshold pulse width to evoke maximal muscle contraction).[162] A pair of surface electrodes was used for both EMG detection and NMES delivery to a target muscle union, and these electrodes were located in the common area of the motor point of the two muscle bellies of the muscle union.[162] A reference electrode (2 × 3 cm^2, Blue Sensor N, Ambu Inc., Ballerup, Denmark) was attached to the skin surface of the olecranon to attenuate the common mode noise.

To facilitate the phasic wrist/hand movements, the ECU-ED and FCR -FD muscle unions were used as voluntary neuromuscular drives to control mechanical assistance and NMES assistance from the system. EMG-triggered control was adopted in this study.[162] Three times the standard deviation (SD) above the EMG baseline in the resting

state was set as the threshold level in each motion phase. In the “wrist extension with the hand open” phase, once the EMG activation level of the ECU-ED reached the preset threshold, NMES was applied to the ECU-ED and mechanical extension torque was provided to the fingers by the inflated pneumatic finger muscles to assist joint extension of the wrist and the fingers throughout the motion phase. In the “wrist flexion with the hand close” phase, as soon as the EMG activation level of the FCR -FD reached the preset threshold, the pneumatic finger muscles were deflated passively and NMES was applied to the FCR-FD to assist joint flexion of the wrist and the fingers throughout the motion phase. The residual voluntary effort from the finger flexors of the paretic limb can facilitate the release of air from the pneumatic muscles during deflation. A detailed description of the assistive control can be found in our previous study on the design of the EMG-driven ENMS for poststroke rehabilitation.[162]

The captured EMG signals were first amplified 1000 times (preamplifier: INA 333; Texas Instruments Inc., Dallas, TX, USA) and filtered from 10 to 500 Hz. These amplified and filtered signals were then sampled using an analog-to-digital converter (AD73360, Analog Devices Inc., Norwood, MA, USA) with a sampling frequency of 1000 Hz for each EMG channel. After digitization, the EMG signals were full-wave rectified and moving-averaged with 100-ms window to obtain the EMG activation level during real-time control.[162]

Real-time control and wireless communication between the control unit and a mobile android application (app) were achieved on a smartphone by using a microprocessor and a Bluetooth module (Bluetooth HC-05, JMoon Technologies., New Delhi, India). The app was designed as the user interface to communicate with the system and provide

visual indications to patients. The designed app emphasized patient convenience, ease of use, large-font instructions with clear options, and straightforward navigation for user-independent operation. A patient can start or stop a training session by simply tapping the button in the app interface. In addition, an emergency stop button of the battery power supply to the control box was also provided as the single switch of the control box to simplify system operation, and to shut down the system in case of an emergency. The training data was recorded by the app and transmitted to the server computer located in the laboratory through a mobile network of 3G or above automatically after a user had exited the app, for telemonitoring the training progress.

4.2.2 Home-based training program

4.2.2.1 Subject recruitment

After obtaining the ethical approval from the Human Subjects Ethics Subcommittee of the Hong Kong Polytechnic University, a total of 15 participants from local districts were screened. Eleven participants with chronic stroke were recruited in this study. The inclusion criteria included (1) at least 1 year after the onset of a singular and unilateral brain lesion due to stroke, (2) discharge from hospital, (3) the spasticity at the elbow, wrist and fingers were ≤3 as measured by the Modified Ashworth Scale (MAS),[77] (4) motor impairments in the affected upper limb ranging from severe to moderate according to the Fugl-Meyer Assessment (FMA; 15 < FMA < 45, with a maximal score of 66 for the upper limb),[40] (5) no visual deficits and the ability to understand and follow simple instructions, as assessed by the Mini-Mental State Examination (MMSE > 21),[78] (6) presence of detectable voluntary EMG signals from the driving muscle on the

affected side (three times the SD above the EMG baseline), (7) presence of active ROM of shoulder from 30° to 80° flexion, (8) presence of passive ROM of wrist from 45° extension to 60° flexion, and the ability of the MCP finger joints to be passively extended to 170°, (9) fulfillment of minimum living environment requirements, including a table measuring at least with 60 × 40 cm^2 as the training space, a bridge chair without wheels, and a 3G or above mobile network coverage at home. Subjects were excluded if they (1) did not fulfill the aforementioned inclusion criteria, (2) were currently pregnant, (3) were epileptic or (4) had an implanted pacemaker. Before the commencement of the clinical trial, written informed consent was obtained from each participant. Figure 4-2 shows the Consolidated Standards of Reporting Trials flowchart of the experimental design.

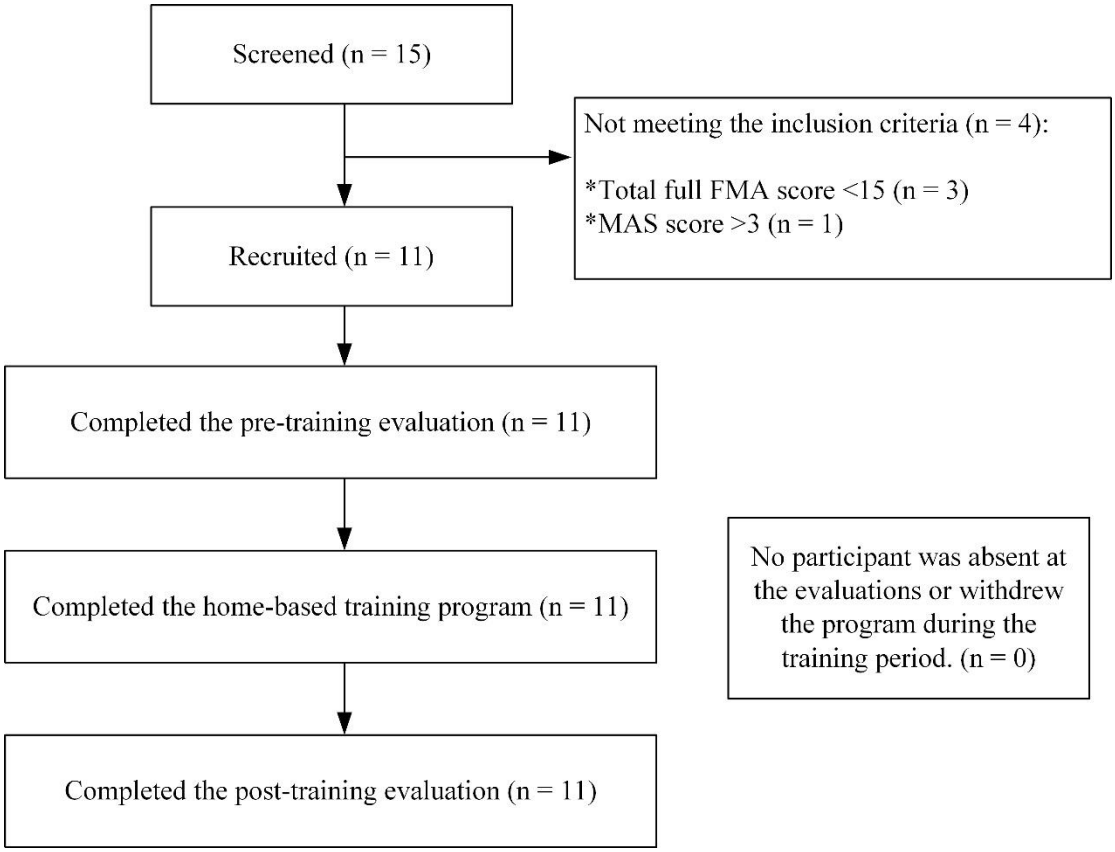

Figure 4-2. The Consolidated Standards of Reporting Trials flowchart of the experimental design.

4.2.2.2 Interventions

The rehabilitation program consisted of a pre-training tutorial and a 20-session upper limb training assisted by the EMG-driven WH-ENMS (at least 60 min/session), with the intensity of 3-5 sessions/week, within 7 consecutive weeks, and with no more than 1 session/day.

Before the training, a pre-training tutorial lasting 30 to 45 minutes on wearing skills, device operation, electrode attachment, and the training protocol was provided to each participant. The procedure of the pre-training tutorial is shown in Figure 4-3. If any participant was not using an Android smartphone or if they did not have a smartphone, they were lent an Android smartphone with the developed app until they completed the training program. Regarding the setting of training parameters, the operator set the training parameters i.e., the EMG triggering levels of the driving muscle unions, maximum inner pressure of the wrist/hand module, and the applied pulse width of NMES for individual participants. These parameters remained fixed throughout the 20-session training. The maximal inner pressure of the wrist/hand module was set to <100 kPa during training, to ensure stability of the pneumatic muscles under repeated inflations and deflations. When placing surface electrodes and reference electrode on the participant's arm, the operator marked those positions on the participant's skin and instructed the participants to retain these markings until the last session. Once the electrode position markings faded, the participants were required to remark them with a marker pen or a ballpoint pen. Moreover, safety instructions were provided during the tutorial.

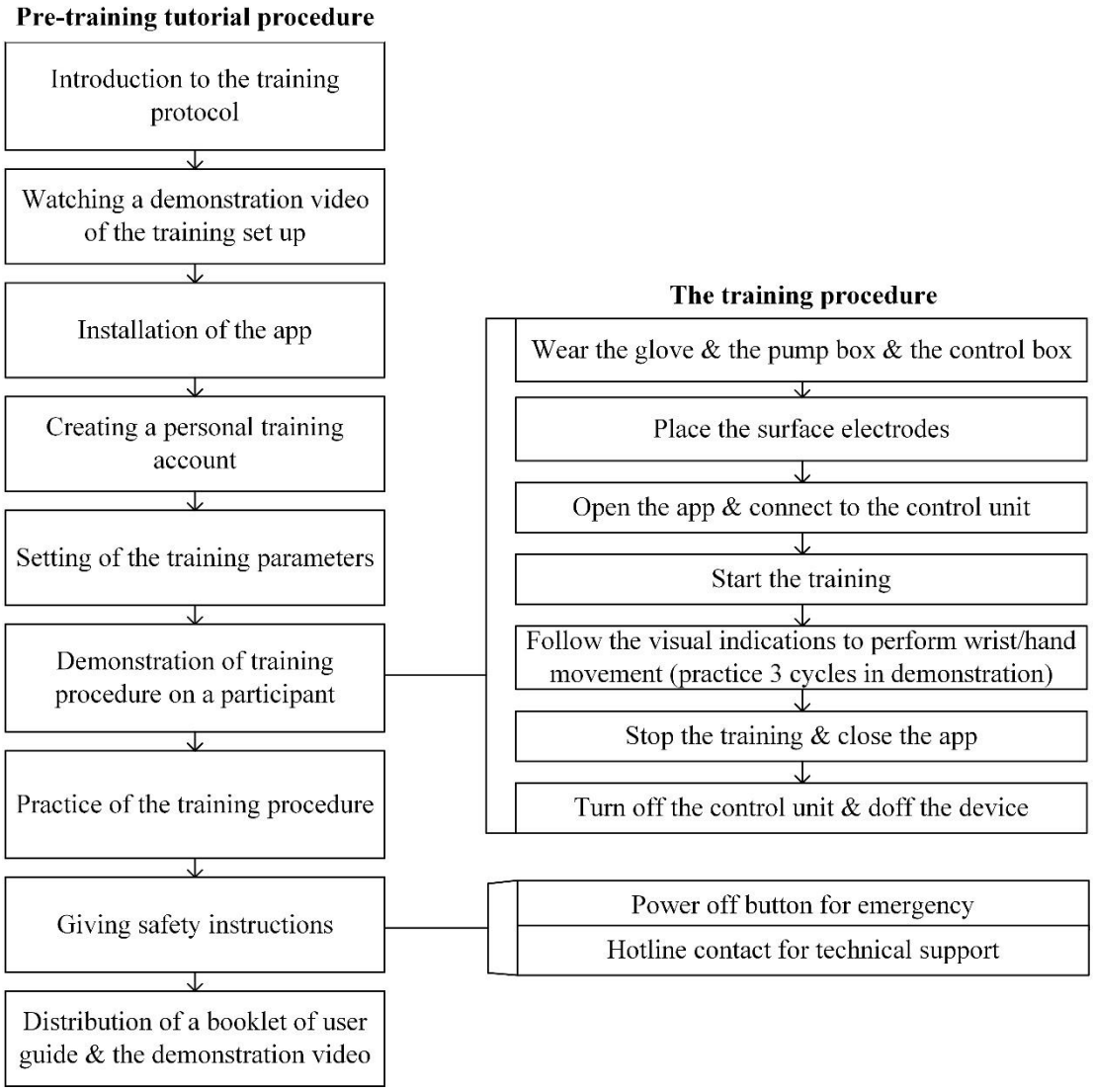

Figure 4-3. Pre-training tutorial procedure.

The training started within 3 days after the tutorial. In each training session, the participants were required to sit at a table and to maintain a vertical distance of 30-40 cm between the table surface and their shoulder (Figure 4-1B-C). The smartphone with the app was positioned on the table and placed in front of the participant at a horizontal distance of 30-60 cm. The participants were required to follow the visual indications displayed on the smartphone screen and perform the repetitive limb tasks assisted by the EMG-driven WH-ENMS on the paretic limb. The participants were then required

to perform 30-min horizontal task and 30-min vertical task (Table 4-1) at their natural speed. A 10-min rest between two consecutive tasks was allowed to prevent muscle fatigue during training sessions.

Task	Description
Horizontal	A participant was instructed to grasp a sponge that was placed on one side of a table near the paretic side of the participant, transport the sponge 50 cm horizontally (i.e., horizontal transportation phase I), release it, grasp it again, move it back to the starting point (i.e., horizontal transportation phase II), and release it.
Vertical	A participant was instructed to grasp the sponge on the table surface, lift it up (i.e., vertical transportation phase I), place it on the top of the shelf (with a vertical distance of 18 cm), grasp it again, place it back on the table surface (i.e., vertical transportation phase II), and release it.

Table 4-1. Descriptions of the required upper limb movements for training tasks.

In this study, the first three training sessions were conducted in the rehabilitation laboratory and were supervised by the experiment operator to reinforce and test the competency of the participants in performing home-based self-help training. In the supervised sessions, nearby professional assistance was provided at varying levels, namely (1) fully assisted, where the operator supported the participants from the training setup and supervised the entire training process in the first session; (2) semi-assisted, where the participants completed the session mainly by themselves, with minimum assistance from the operator in the second session; and (3) independent-with-observation, where the participants completed the training session independently under close observation by the operator. An additional semi-assisted session was offered to participants who were not ready for the independent-with-observation session. During

the third session, the operator marked the competency checklist (Table 4-2) to assess the participant's competency in conducting home-based training with the system. Once the participants correctly demonstrated all of the technical items listed on the competency checklist, they were required to start the home-based training for the remaining sessions. If a participant had a personal caregiver, the caregiver was also invited to attend the tutorial and training sessions and allowed to provide assistance with the setup. Figure 4-4 shows the timeline of the EMG-driven WH-ENMS-assisted home-based self-help upper limb training program.

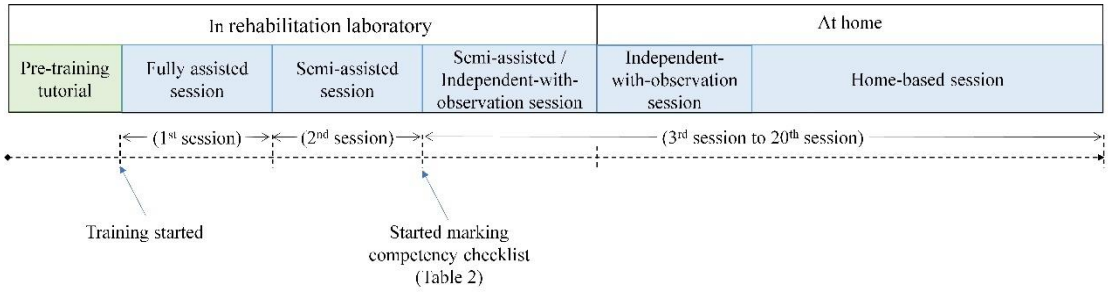

Figure 4-4. Timeline of the EMG-driven WH-ENMS-assisted home-based self-help upper limb training program.

Is the participant able to demonstrate the following abilities appropriately when using the system?	Yes	No
Don and doff the device		
Turn on and turn off the device		
Login and logout of the personal training account		
Connect the app and the device		
Attach the electrodes onto their arm		
Start and stop the training		
Recharge the device		
Is the participant able to demonstrate the following abilities appropriately during the training?	Yes	No
Safely and correctly perform all of the training tasks in a session		
Place two markers at a horizontal distance of 50 cm on the table for the horizontal task		
Place the shelf with the correct setting for the vertical tasks		
Understand the safety precautions and warnings associated with device usage during training		
If the participant joins with a caregiver, the caregiver is allowed to assist with the training setup. If the answer is “No” for any item, the participant is deemed to be not competent to perform the home-based training with the system. Otherwise, the participant is deemed as competent. Experiment operator: _____ Signature: _____ Date: Number of current session:		

Table 4-2. Competency checklist.

4.2.2.3 Logistics Management of Home-based Training

Prior to the commencement of the home-based training, the operator first arranged the training schedules for the remaining sessions agreed by a participant, and subsequently delivered the system with a battery charger and training props (e.g., a sponge and a shelf) to the participants' homes. In the first home-based session, the operator visited the participants' homes to inspect environmental safety (e.g., training space and nearby electricity) and then observed the entire session to ensure consistency with the session in the laboratory. The participants were required to complete the remaining sessions at home without on-site professional supervision (home-based sessions). The participants could change the training schedule occasionally by informing the operator 1 day in advance so that the operator could arrange a make-up session for the participant without violating the protocol intensity, i.e., 3-5 sessions/week. Finally, the participants were required to return the system to the research team during their post-training evaluation visit to the laboratory, which was scheduled 1 day after the last training session.

The logistics management data recorded by the developed app, including the number of completed wrist/hand movement cycles, total training time, and completion date/time point of a session, were automatically transmitted via a mobile network to the server computer located in the laboratory. The data were reviewed by the operator through an encrypted network which required the operator to enter a pre-set login account and password [163], for telemonitoring the training progress of the participants. The experiment operator remotely monitored the completion of each home-based session based on the participants' commitment to the training schedule. Once a missing session was found, the operators contacted the participant by telephone to schedule a

make-up session.

If there was any technical issue during the home-based sessions, the participants were able to inform the experiment operator immediately through a phone call or a message. A backup system was prepared for each participant and used to replace the malfunctioning system. The participants were required to return the malfunctioning system to the laboratory and have it replaced with the backup system in 1 working day.

4.2.3 Evaluation of training outcomes

Clinical assessments, EMG measurements, and kinematic measurements were adopted to investigate the rehabilitation outcomes of the home-based self-help upper limb training assisted by the EMG-driven WH-ENMS. All evaluations were conducted at the laboratory. All of the participants underwent evaluations just before the pre-training tutorial (i.e., pre-training evaluation) and 1 day after the last training session (i.e., post-training evaluation).

4.2.3.1 Clinical assessments for functional evaluation

In this study, clinical assessments were used to evaluate the motor functional improvements of each participant and were conducted by a training-blinded assessor. The adopted clinical assessments included (1) the FMA that the full score is 66 for the upper limb assessment, which has been sub-scaled into shoulder/elbow (42/66) and wrist/hand (24/66),[80] was adopted to measure the motor functional impairment in voluntary limb movements; (2) the Action Research Arm Test (ARAT),[81] was applied to evaluate the upper limb voluntary functions with a focus on the finger activities; (3)

the Wolf Motor Function Test (WMFT),[82] was used to assess the functional ability and motion speed of the upper limb in daily tasks; (4) the Motor Functional Independence Measure (FIM),[83] was adopted to evaluate the basic quality of participant's ADLs; and (5) the MAS[77] on the flexors related to the elbow, wrist, and fingers, was used to measure the poststroke spasticity at the related joints.

4.2.3.2 Evaluation of muscular coordination in the upper limb by EMG

Two EMG parameters were used to obtain quantitative information on the muscle activation and coordination patterns of the paretic limb. They were (1) the EMG activation level of each target muscle and (2) the EMG co-contraction index (CI) between muscle pairs.[67, 68] EMG recordings of the maximum voluntary contractions (MVCs)[127] and a bare arm test[75, 107] were performed during the evaluation. EMG electrode pairs (2 × 3 cm^2, Blue Sensor N, Ambu Inc., Ballerup, Denmark) were attached to the skin surface of the following target muscle unions or muscles of the paretic limb: abductor pollicis brevis (APB), FCR-FD muscle union, ECU-ED muscle union, biceps brachii (BIC) muscles, and triceps brachii (TRI) muscles (the configuration specified in a previous study[108] was used). The bare arm test was similar to the motion tasks in the training. The participants were required to use their paretic limbs to perform the horizontal and vertical tasks (Table 4-1) without any assistance from the system and complete the tasks at their natural speed, with the seating arrangement shown in Figure 4-5. Both the lateral and vertical tasks were repeated thrice. There was a 2-min rest between two consecutive contractions to prevent muscle fatigue. In each task, the EMG recording was started once the participant' hand touched

the sponge and ended once all of the fingers left the sponge at the starting point. A 10-s maximum time limit was set at the end of the attempt to perform the release action during the tasks.[107, 128] If the participants could not release the sponge within 10-s during the tasks, they could use their unaffected hands to remove the sponge. Most of the participants (n = 8) could not release the sponge by using their paretic hands due to the spasticity at the flexors and the weakness at the extensors of the distal joints.[142, 143] In the post-training evaluation, two of them could release the sponge without assistance from their unaffected hands.

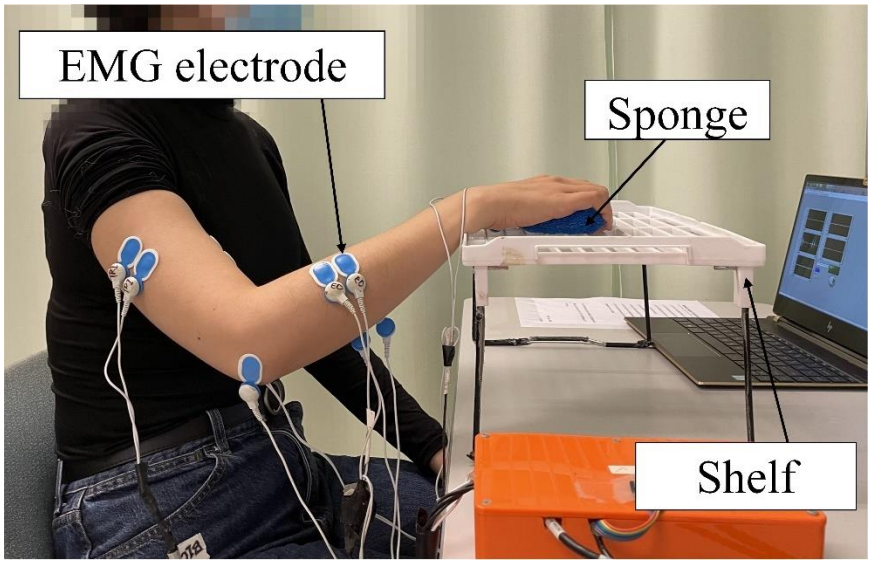

Figure 4-5. Configuration of EMG recording during the bare arm test.

The collected EMG signals were first amplified with a gain of 1000 (amplifier: INA 333, Texas Instruments Inc., Dallas, TX, USA), band-pass filtered from 10 to 500 Hz, and then sampled at 1000 Hz for digitization for offline processing.[128]

The EMG activation level of a muscle was calculated as follows:

$$\overline{\mathrm{EMG}} = \frac{1}{T}\int_0^T EMG_i(t)dt\ , \qquad (Eq.1)$$

where $\overline{\mathrm{EMG}}$ refers to the average EMG envelope value of muscle *i*, $\mathrm{EMG_i(t)}$ is the EMG envelope signal obtained after normalization with respect to the EMG MVC value of the muscle, and *T* is the length of the signal.

The CI between a pair of muscles can be expressed as follows:

$$\mathrm{CI} = \frac{1}{T}\int_0^T A_{ij}(t)dt\,, \qquad (Eq.2)$$

where $A_{ij}(t)$ is the overlapping activity of EMG linear envelopes for muscles *i* and *j*, and *T* is the length of the signal. An increase in the CI value represents an increased co-contraction of a muscle pair (broadened overlapping area), and a decrease in the CI value indicates a decreased co-contraction of a muscle pair (reduced overlapping area).

4.2.3.3 Evaluation of movement smoothness and compensatory trunk movement

Three-dimensional motion analysis was performed to quantify the kinematic performance of the upper limb, and this was used as an outcome measure to evaluate impaired movement after stroke.[121, 122] Two kinematic parameters, (1) number of movement units (NMUs) and (2) maximal trunk displacement (MTD),[164, 165] were adopted to obtain quantitative information about movement smoothness and compensatory trunk movement. During motion capturing, the bare arm test (Table 4-1) was conducted. The participants were required to repeat both the lateral and the vertical tasks thrice. There was a 2-min break between two consecutive contractions to prevent muscle fatigue. A total of 25 spherical reflective markers (12-mm diameter for each) were attached to the skin of the upper limb and the body trunk in accordance with the

upper limb model of the BodyBuilder model (Vicon Motion Systems, Oxford, UK[120]) (Figure 4-6). The marker positions were captured using an eight-camera motion system (Vicon Motion Systems, Oxford, UK) at a sampling frequency of 250 Hz. A Vicon Workstation (Vicon Motion Systems, Oxford, UK) with three-dimensional reconstruction software (Vicon Nexus and BodyBuilder, Oxford, UK) was used to anatomically label, filter, and apply the upper limb model.[120-122] The positions and velocities of the markers during the motion were thus obtained in all trials.[123]

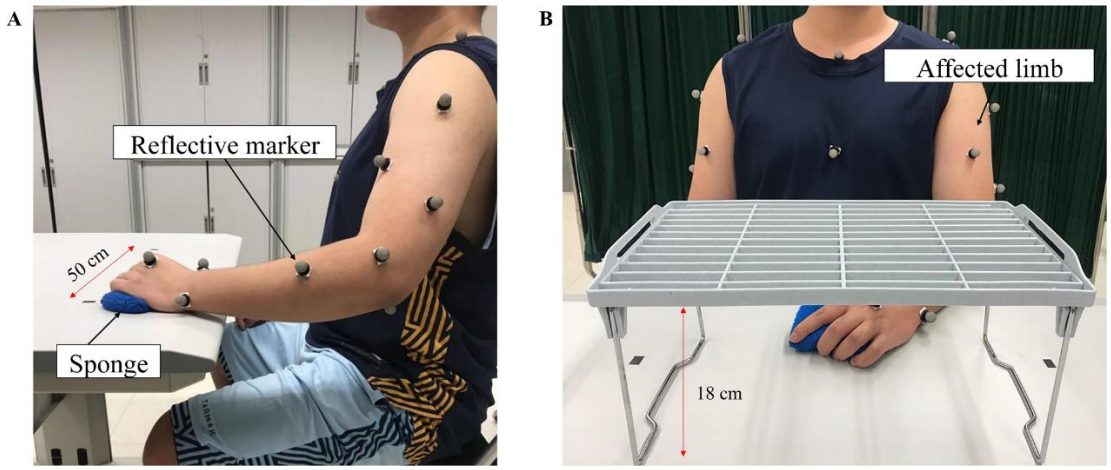

Figure 4-6. Experimental setup for (A) the horizontal task and (B) vertical task during three-dimensional motion capturing.

The tangential velocity profile of the hand marker (placed on the metacarpophalangeal joint of the middle finger) in the transporting phases of the tasks (Table 4-1) was used to compute the NMUs.[164] In a trial, the recording started once the hand of a participant left the target position (i.e., table surface or the top of the shelf) and ended once the hand of the participant touched another target position (i.e., table surface or the top of the shelf).

The NMUs can be expressed as follows:

$$\begin{cases} NMUs = \sum Count \\ Count = \begin{cases} 1 \text{ , } if \ \ max - min \ > \ 0.15(MAX) \\ 0 \text{ , } else \end{cases} \end{cases} , \qquad (Eq. 3)$$

where $NMUs$ is the cumulative counted number of a signified movement unit $Count$. A movement unit was signified once an increase had emerged between the adjacent minimum velocity min and maximum velocity max and had exceeded a threshold level that was 15% of the maximal velocity MAX in the trial. NMUs has been used to quantify movement smoothness.[164] An increase in NMUs indicates decreased movement smoothness.

The MTD can be formulated as follows:

$$\begin{cases} MTD = MAX\ \{D(t)\} \\ D(t) = \sqrt{\{(x_t - x_0)^2 + (y_t - y_0)^2 + (z_t - z_0)^2\}} \end{cases} , \qquad (Eq. 4)$$

where MTD refers to the maximal displacement $MAX\ \{D(t)\}$ of the thorax marker (placed on the jugular notch where the clavicles meet the sternum) from the initial position during the entire motion task.[164] Each calculated displacement $D(t)$ was the distance between the initial position (x_0, y_0, z_0) and each recorded position (x_t, y_t, z_t) in a trial.[166] The recording of the marker position was started when a participant touched the sponge and ended when the participant released the sponge at the starting point (all of the fingers left the sponge). MTD has been used to quantify compensatory trunk movements during limb movements, where a decrease in MTD indicates a reduction in compensatory trunk movement when the limb tasks are being performed.[164] The MTD can also be used to determine whether the smoother movement is the result of the motor function recovery or the compensatory strategies adopted by participants.[167] A 20-min break was provided between two consecutive measurements to avoid muscle fatigue.

4.2.4 Statistics

The normality tests on the clinical scores, EMG parameters and kinematic parameters were evaluated using the Lilliefors method with a significance level of 0.05.[84] The MAS exhibited significance in the normality test ($P < 0.05$), and the FMA, ARAT, WMFT, FIM, EMG parameters and kinematic parameters exhibited nonsignificant probabilities ($P > 0.05$). Wilcoxon's signed rank test was performed on the MAS using a paired comparison of the scores before and after the training. Paired-sample *t* test was used to detect the differences in the FMA, ARAT, WMFT, FIM, EMG data and kinematic data before and after the training. The primary outcome of this study was the FMA. The other clinical scores, EMG parameters, and kinematic parameters were secondary outcomes. The statistically significant level of 0.05 was used for all tests in this study. The significance levels at 0.01 and 0.001 were indicated as well.

4.3 Results

All of the recruited participants (n = 11) completed the home-based self-help upper limb training assisted by the EMG-driven WH-ENMS. The demographic data of the participants are shown in Table 4-3.

Subjects No.	Gender Female/Male	Stroke Types Hemorrhagic/ Ischemic	Side of Hemiparesis Left/ Right	Age (years) Mean ± SD	Years after onset of stroke Mean ± SD
11	6/5	5/6	8/3	57.6±13.2	13.4±10.4

Table 4-3. Demographic characteristics of the patients with stroke recruited for the home-based self-help upper limb training program (n =11).

4.3.1 Independency in self-help upper limb training at home

In this study, all of the participants were determined as having sufficient competence to perform the home-based training after the third session, and no additional semi-assisted session was required by them. Six of the participants completed the training at home independently, whereas the others completed the training with partial assistance from their caregivers at home. Four of the participants conducted and completed the home-based self-help training during the COVID-19 pandemic in Hong Kong. No adverse event (e.g., pain or injury) during or after the training was reported by either the experiment operators or the participants throughout the study period.

According to the logistic data captured using the app, the average training frequency in the 20-session training was 3.73 ± 0.75 (mean ± SD) sessions/week, with a range of 3–5 sessions/week. Variability was observed in the duration of the home-based training, with an average session duration of 63.0 ± 1.90 (mean ± SD) min/session (ranging from 60 to 66 min/session), and average complete wrist/hand movement cycles per session of 116 ± 8.72 (mean ± SD). The earliest and latest training times were 07:00 and 22:00, respectively. The peak training hours were between 14:00 to 16:00 and 19:00 to 21:00, with more than 80% of the home-based sessions being conducted during those periods. Five participants encountered technical issues during the home-based training sessions, among which three were related to broken leads because of excessive pulling on the leads and two were related to air leakage from the musculoskeleton hand due to hard and repeated squeezing of the pneumatic muscles during inflation. These problems were solved within 1 working day, and the related components were further reinforced. Furthermore, the malfunctioning systems were also replaced with backup systems

within 1 working day.

4.3.2 Training outcomes of the home-based self-help program

4.3.2.1 Clinical assessments

Table 4-4 lists all of the clinical scores measured in this study (i.e., the means and 95% confidence intervals of each clinical assessment, together with the paired-sample *t* test/ Wilcoxon's signed rank test probabilities with effect sizes (EFs) for evaluations before and after the training). The comparison of the clinical scores measured before and after the training is shown in Figure 4-7. In Figure 4-7A, a significant increase was found after the training in the FMA full score, FMA shoulder/elbow, FMA wrist/hand, ARAT, WMFT score, and WMFT time ($P < 0.05$, paired-sample *t* test). In Figure 4-7B, a significant decrease in the MAS scores was observed after the training at the elbow, the wrist and the fingers ($P < 0.05$, Wilcoxon's signed rank test).

Evaluation	Pre	Post	Paired-sample *t* test	
	Mean (95% Confidence interval)		P-value	Cohen's *d*
FMA				
Full Score	33.4 (30.2~39.7)	44.5 (41.3~51.0)	<0.001***	1.84
Shoulder/Elbow	21.5 (19.6~25.4)	28.6 (26.6~32.7)	0.002**	1.29
Wrist/Hand	11.8 (10.3~14.8)	15.9 (14.4~18.9)	0.002**	1.29
ARAT	19.3 (15.7~26.5)	26.7 (22.7~34.8)	0.001***	1.34
WMFT				
Score	39.2 (34.8~47.9)	45.9 (41.6~54.6)	0.003**	1.16
Time	51.6 (45.2~64.5)	45.7 (40.1~57.0)	0.033*	–0.75
FIM	65.6 (65.1~66.8)	65.7 (65.2~66.9)	0.341	0.30
MAS			**Wilcoxon's signed ranks test**	
			P-value	r
Elbow	2.18 (1.59~2.77)	1.49 (0.82~2.17)	0.026*	–0.67
Wrist	1.95 (1.17~2.72)	1.18 (0.48~1.89)	0.026*	–0.67
Finger	1.98 (1.39~2.58)	1.40 (0.73~2.07)	0.024*	–0.68

Table 4-4. Means and 95% confidence intervals of each measurement in the clinical assessments and the probabilities and estimated effect sizes in the statistical analyses. Differences with statistical significance are denoted by * ($P \leq 0.05$), ** ($P \leq 0.01$), and *** ($P \leq 0.001$).

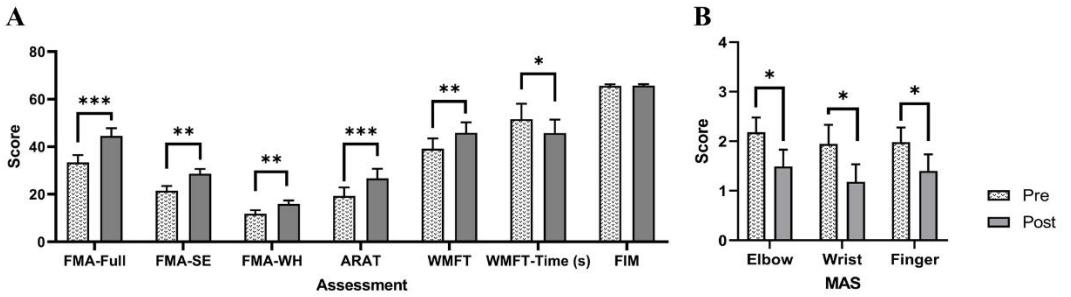

Figure 4-7. The measured clinical scores of the (A) FMA, ARAT, WMFT and FIM, and (B) the MAS before (Pre) and after (Post) the training represented by means and standard errors. Significance levels are indicated by * ($P \leq 0.05$), ** ($P \leq 0.01$), and *** ($P \leq 0.001$).

4.3.2.2 EMG parameters

Table 4-5 lists the measured EMG parameters (i.e., the means and 95% confidence intervals of each clinical assessment, together with the paired-sample *t* test probabilities with EFs of the evaluation before and after the training). Figure 4-8 illustrates the EMG parameters (i.e., the normalized EMG activation level and the normalized CI) that were statistically significant before and after the training. A significant decrease in EMG activation level was detected in the APB and FCR-FD ($P < 0.05$) after the training (Figure 4-8A). A significant reduction of CI in the muscle pairs of ECU-ED/FCR-FD, ECU-ED/BIC, FCR-FD/APB, FCR-FD/BIC, FCR-FD/TRI, APB/BIC and BIC/TRI ($P < 0.05$) was found after the training (Figure 4-8B). No significant increase or decrease was observed in the EMG parameters of the other target muscles and muscle pairs.

EMG parameters	Pre	Post	Paired-sample *t* test	
	Mean (95% Confidence interval) (%)		P-value	Cohen's *d*
Normalized EMG activation level				
APB	10.8 (7.61~14.1)	6.25 (3.60~8.91)	0.001***	–0.83
ECU-ED	9.84 (7.45~12.2)	7.44 (5.20~9.68)	0.17	–0.30
FCR-FD	6.52 (4.73~8.32)	3.21 (2.26~4.16)	<0.001***	–1.00
BIC	7.71 (5.92~9.49)	6.12 (4.89~7.36)	0.11	–0.36
TRI	7.05 (3.89~10.20)	5.77 (3.32~8.23)	0.48	–0.15
Normalized CI				
APB/ ECU-ED	7.19 (4.65~9.72)	4.94 (2.56~7.32)	0.18	–0.30
APB/ FCR-FD	5.98 (4.10~7.86)	2.58 (1.64~3.51)	0.001***	–0.79
APB/BIC	5.82 (4.24~7.40)	2.91 (2.17~3.64)	0.003**	–0.72
APB/ TRI	6.04 (3.16~8.91)	4.56 (2.26~6.85)	0.35	–0.20
ECU-ED/FCR-FD	5.34 (3.83~6.86)	2.69 (1.89~3.48)	0.002**	–0.76
ECU-ED/BIC	4.97 (4.14~5.81)	3.60 (2.81~4.40)	0.022*	–0.53
ECU-ED/TRI	4.18 (3.09~5.26)	3.88 (2.39~5.37)	0.684	–0.09
FCR-FD/BIC	4.37 (3.15~5.59)	2.42 (1.75~3.08)	0.002**	–0.77
FCR-FD/ TRI	3.80 (2.59~5.01)	2.17 (1.42~2.92)	0.005**	–0.67
BIC/TRI	6.64 (4.80~8.49)	4.59 (3.54~5.63)	0.039*	–0.47

Table 4-5. Means and 95% confidence intervals of each measurement in the EMG parameters as well as the probabilities and estimated effect sizes in the statistical analyses. Differences with statistical significance are denoted by * ($P \leq 0.05$), ** ($P \leq 0.01$), and *** ($P \leq 0.001$).

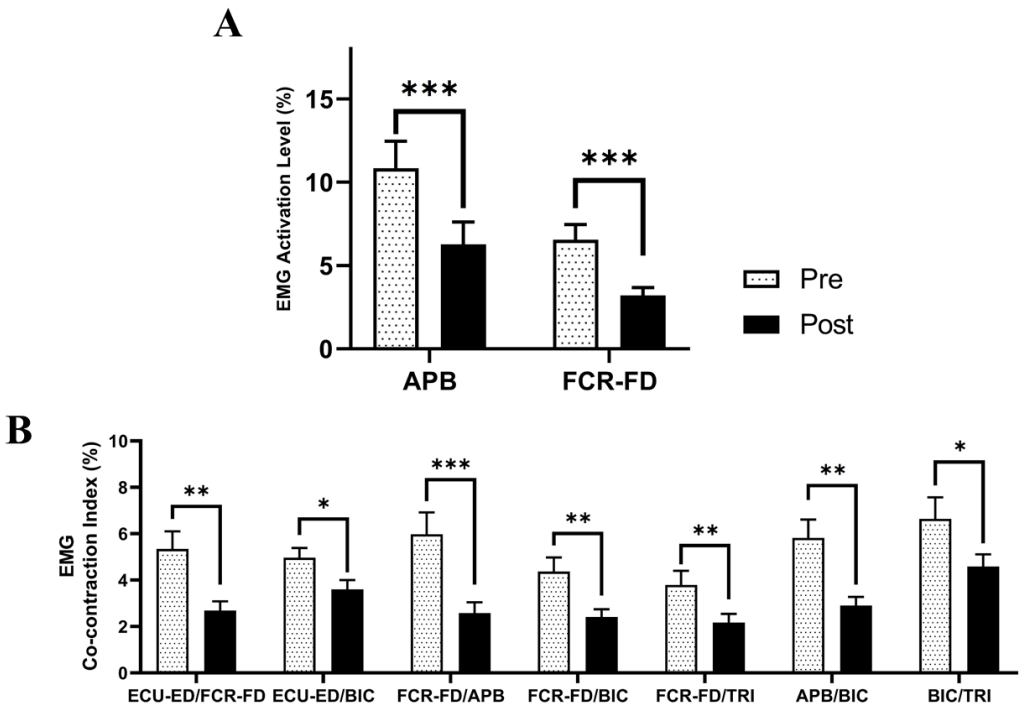

Figure 4-8. (A) EMG activation levels of the APB and FCR–FD during the bare hand evaluations, and (B) the EMG CI between the FCR–FD and ECU–ED, ECU–ED and BIC, FCR–FD and APB, FCR–FD and BIC, FCR–FD and TRI, APB and BIC, and BIC and TRI during the bare hand evaluations before (Pre) and after (Post) the training represented by means and standard errors. Significance levels are indicated by * ($P \leq 0.05$), ** ($P \leq 0.01$), and *** ($P \leq 0.001$).

4.3.2.3 Kinematic parameters

The measured kinematic parameters are listed in Table 4-6 (i.e., the means and 95% confidence intervals of each clinical assessment, together with the paired-sample *t* test probabilities with EFs of the evaluation before and after the training). Figure 4-9A-B shows the representative velocity profiles of the horizontal and vertical tasks before and

after the training of a participant with respect to the three-dimensional trajectory of the hand marker during the transport phases. A significant decrease in NMUs was observed after the training (Figure 4-9C; $P < 0.05$). Figure 4-10A-B illustrates the representative displacement profiles of a participant during horizontal and vertical tasks before and after the training with respect to the three-dimensional trajectory of the thorax marker throughout the entire trial. A significant reduction in MTD was found after the training (Figure 4-10C; $P < 0.05$).

Kinematic parameters	**Pre**	**Post**	**Paired-sample *t* test**	
	Mean (95% Confidence interval)		P-value	Cohen's *d*
NMUs	26.8 (22.3~31.3)	17.6 (14.8~20.4)	<0.001***	–1.06
MTD	149 (126~172)	125 (101~149)	0.016*	–0.56

Table 4-6. Means and 95% confidence intervals of each measurement in the kinematic parameters as well as the probabilities and estimated effect sizes in the statistical analyses. Differences with statistical significance are denoted by * ($P \leq 0.05$), ** ($P \leq 0.01$), and *** ($P \leq 0.001$).

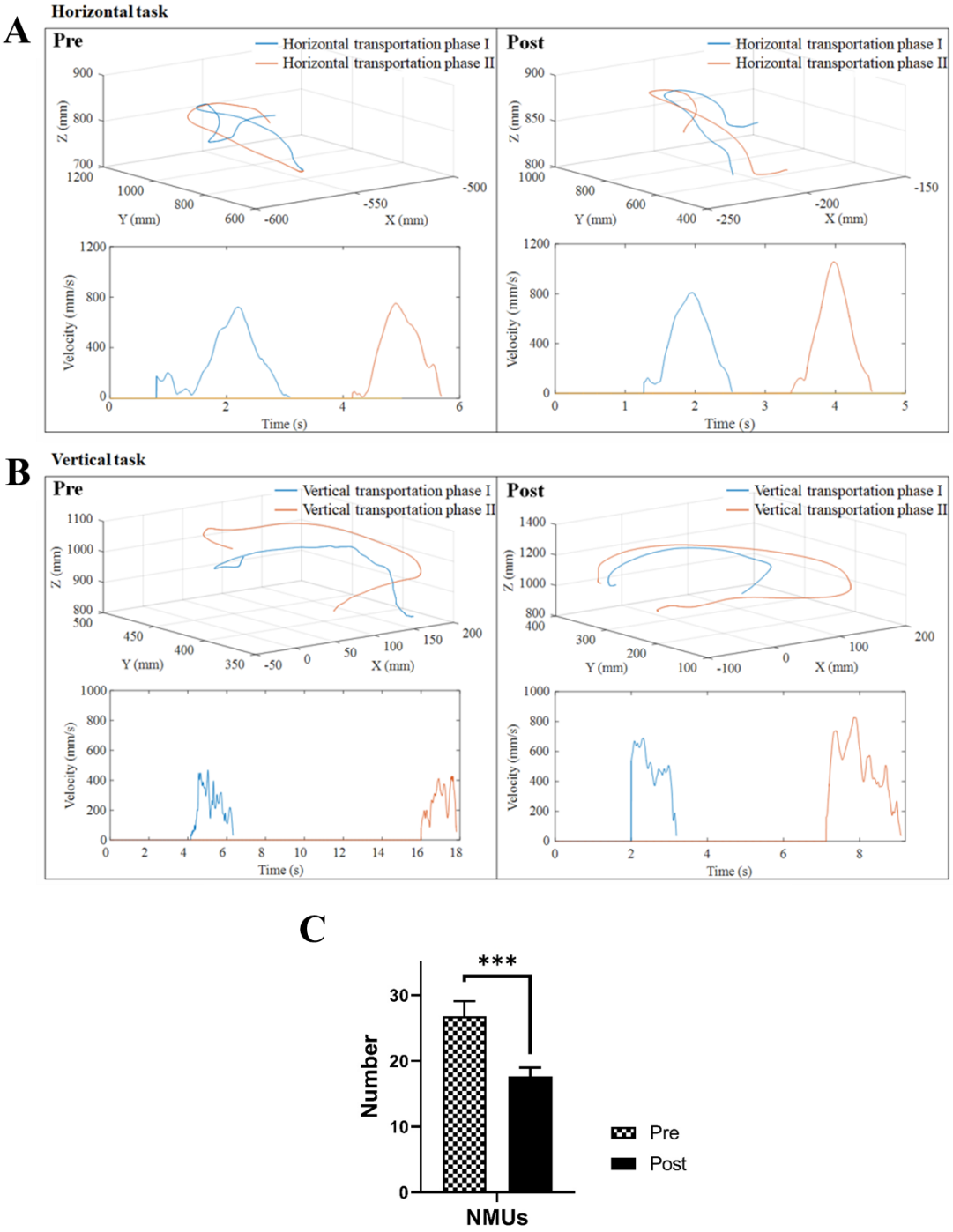

Figure 4-9. Representative measured trajectory of the hand marker during the transport phases in (A) the horizontal task and (B) vertical task for a participant, and the related velocity profiles of the trial before and after training. (C) The NMUs before (Pre) and after (Post) the training represented in terms of the mean and standard error. Significance levels are indicated by *** ($P \leq 0.001$).

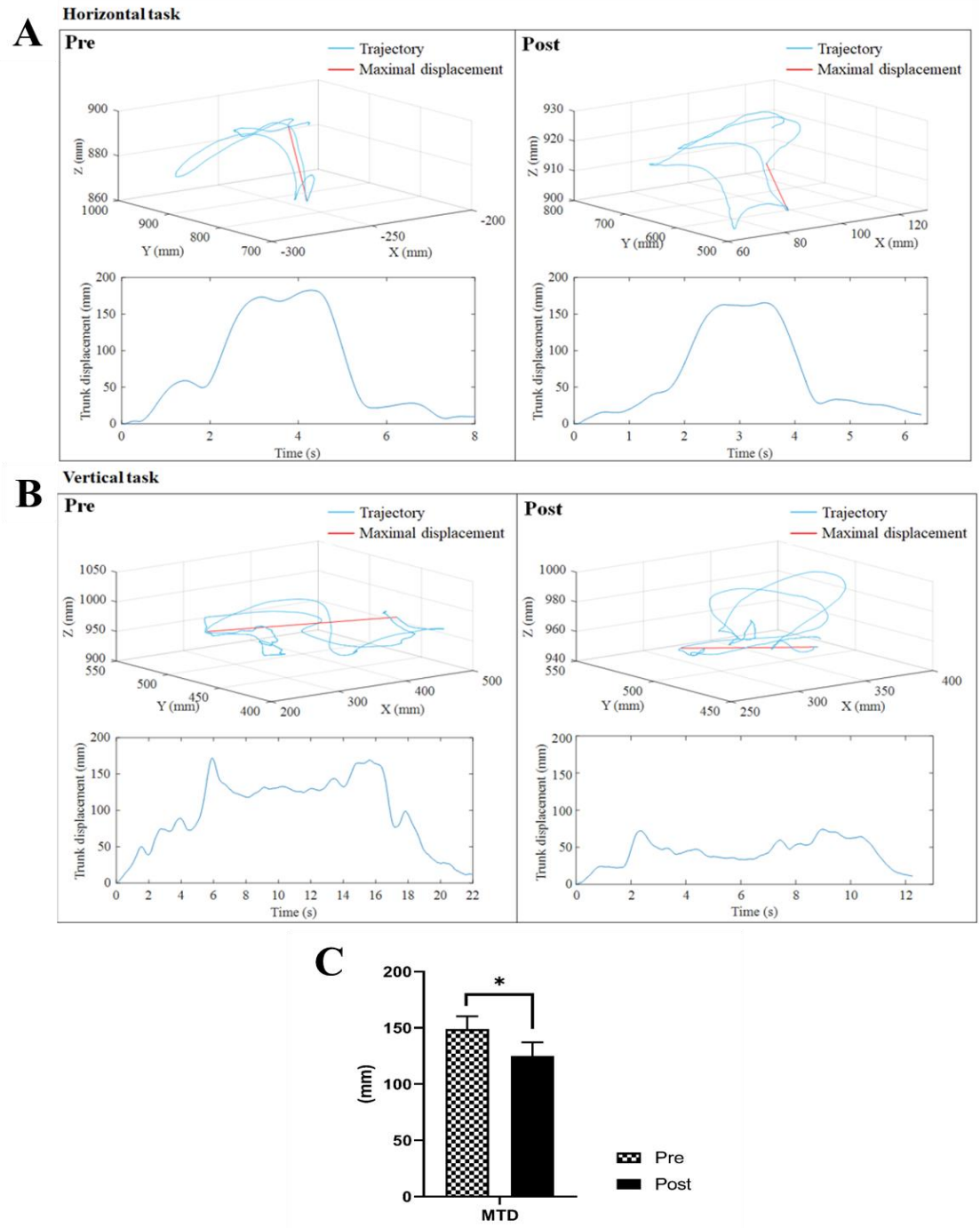

Figure 4-10. Representative measured trajectory of the thorax marker over the entire trial for (A) the horizontal task and (B) vertical task for a participant, and the related displacement profiles in the trial before and after the training. (C) The MTD before (Pre) and after (Post) the training represented in terms of the mean and standard error. Significance levels are indicated by * ($P \leq 0.05$).

4.4 Discussion

The results of this study support the hypothesis that it is feasible to use EMG-driven WH-ENMS to support the home-based self-help upper limb training of discharged participants with chronic stroke. After 20-session training, motor function improvements associated with improved clinical scores, EMG parameters, and kinematic parameters were observed in all of the participants.

4.4.1 Training outcomes of the home-based self-help program

4.4.1.1 Clinical assessments

The significant increase in the FMA (shoulder/elbow and wrist/hand) score indicated an improvement in voluntary motor control of the entire upper limb after the training, especially on the joint stability and ROMs at the related joints on the paretic limb (Figure 4-7A). A significant increase of 11 points in the FMA full score (max 66) was observed after the training (mean admission score: 33 points). Compared with our previous trial on self-help upper limb training assisted by the EMG-driven ENMS in the laboratory,[162] motor improvement exhibited a significant increase of 14 points in in the FMA full score after the training (mean admission score: 34 points). In both trials, 20 training sessions were provided, and the participants were required to practice multi-joint coordinated upper limb tasks during these sessions. The additional motor improvement in our previous trial might ascribable to the (1) longer training duration (i.e., an additional 30 min per session) and (2) the provision of additional mechanical

extension torque and NMES assistance to the proximal joints during training.[162] Compared with home-based wrist/hand training assisted by a pneumatic system (Hand Mentor Pro),[168] motor improvement in FMA exhibited a significant increases of 9 points after the training (mean admission score: 34 points). As reported by the study,[168] the participants underwent training for 3 h per day, 5 days per week for 8 weeks, and the session duration was longer and the training intensity was higher than in our home-based training. The additional improvement in the voluntary motor control of the upper limb was probably due to the involvement of voluntary efforts from the affected limb and NMES during the wrist/hand movements. In addition, the recovery progress of the patients might have been accelerated due to the combined NMES-robot treatment.[51, 85] The significant increase in the ARAT score indicated the improvements in the hand function of the participants when handling different objects and coordination of the fingers for fine precision grasping (Figure 4-7A).

The increased WMFT scores suggested an overall improvement in the entire upper limb and increased ability to perform daily activities (Figure 4-7A). The reduced time for conducting WMFT tasks (WMFT time) implied an improvement in movement efficiency and improved muscle coordination in the upper limb (Figure 4-7A). In our previous trial on the training assisted by EMG-driven ENMS in the laboratory, no significant improvement was observed in the WMFT scores after the training.[162] One key difference between the training tasks in both studies was that the training tasks in this study involved grasping/releasing an object (i.e., transporting a sponge to different positions). Because the WMFT measures both the motion speed and the functional ability of the upper limb in performing daily tasks, the additional improvement in the WMFT scores might ascribable to the fact that the training tasks in this study were more

similar to daily activities than those of the previous study.

A significant improvement in the ability to perform daily activities was observed (as manifested in the increased WMFT scores and decreased WMFT time), but the improvement in the functional use of ADLs was not confirmed by the FIM scores. This suggested that the regained motor functions might not be translated into the functional use of the paretic limb to perform ADLs, even though the ability of performing daily tasks increased after the training. This was probably due to the two following characteristics of patients with chronic stroke: (1) learned nonuse could have become a habit, and the limb may not be used in functional activities although the individual has ability to move it,[18] and (2) the unaffected limb attempts to execute all of the motor actions required for daily living.[88] It is suggested that outpatient rehabilitation should start as early as possible to inhibit the development of learned nonuse to ensure that the motor gains could translate into the functional use of the affected limb in ADLs.

The significant decrease in MAS score at the flexors of the elbow indicated that the spasticity of the elbow joint was reduced (Figure 4-7B). The significantly reduced MAS scores at the flexors of the wrist and fingers indicated a release of spasticity of the distal joints (Figure 4-7B). The reduced MAS score reflected a superior control over synergic muscle activity and a decrease in compensatory muscular activity.[18, 71] The decrease in the MAS scores of the elbow, wrist, and finger joints implied improved muscle coordination and joint stability of the proximal and distal joints during arm reaching, which was consistent with the observations in the FMA.

4.4.1.2 EMG parameters

A reduction in excessive muscle activities and improved muscle coordination was revealed by the decrease in the EMG activation levels at the flexors of the distal joints, co-contractions between the antagonist muscle pairs related to the wrist/hand and elbow, and co-contraction between the proximal and the distal joints (Figure 4-8). The decreased EMG activation levels could be attributed to the reduced spasticity that led to a reduction in the extra muscle activities.[89] The significant decrease in the EMG activation levels of the APB and the FCR-FD muscles reflected a release of muscle spasticity at the fingers and the wrist, which was manifested in decreased MAS scores in the distal joints. The reduction of excessive muscle activities of the APB and the FCR-FD suggested an improvement in muscle coordination and voluntary motor controls during grasp and release movements, which was consistent with the findings in the FMA. A significant reduction in the CI of the ECU-ED/FCR-FD and the BIC/TRI muscle pairs was observed, indicating improved coordination between the flexors and extensors at the related joints, and improved independence in muscle contraction after the training. The significant disease in the CI of the ECU-ED/BIC, FCR-FD/BIC, FCR-FD/TRI, APB/BIC muscle pairs implied a release in the muscle co-contraction between the proximal and distal joints during arm reaching/withdrawing and grasping/releasing. A significant reduction in the CI of the FCR-FD/APB muscle pair was observed, suggesting a release in muscle co-contraction between the distal joints and the thumb, which contributed to the motor improvements in hand grasping, as manifested in the increased ARAT scores.

4.4.1.3 Kinematic parameters

A significant decrease in NMUs was found after the training, indicating increased smoothness of movement (Figure 4-9). Oscillatory velocity profiles with multiple peaks were observed in the performance of a limb task of a patient with stroke using a paretic limb, as opposed to the smooth bell-shaped velocity profile with one predominant peak of the nonparetic limb.[165] These peaks reflect repetitive acceleration and deceleration when performing the limb task, which was due to the limited ability of patients with stroke patients to produce accommodative joint torque to maintain muscle tone during multi-joint coordinated limb movements.[167] The increased smoothness suggested an improvement in fine motor control[164, 169] and improved inter-joint coordination,[169] which was consistent with the observations in the cross-joint CIs. It is a common observation that stroke patients rely on compensatory strategies that involving the trunk to overcome limb impairments during arm reaching associated with distal movements.[18, 170, 171] The significant reduction in MTD revealed a reduction in compensatory trunk movements when performing the multi-joint coordinated limb task, especially during object transportation (Figure 4-10). The reduced requirement of trunk involvement to assist object transportation suggested an improvement in muscle strength in the shoulder and elbow and a release of spasticity in the elbow.[172]

Motor improvements in the entire upper limb were found after the training. In this study, the system provided wrist/hand assistance to the participants when they practiced the multi-joint coordinated upper limb task. It was reported that motor improvements in both the proximal and distal joints could be obtained through physical training involving the multi-joint coordinated task.[173] Furthermore, the introduction of NMES

into the distal joints could promote motor coordination between the proximal and distal joints during rehabilitation, which could facilitate the improvement in the entire upper limb.[51, 85, 107] Despite the relatively small populations recruited, we observed consistent results on the motor improvements achieved after the training. In our future work, large scale, multi-center randomized controlled trials (RCTs) with long-term follow-up (e.g., 6-month follow-up) will be conducted.

4.4.2 Independency in self-help upper limb training at home

Currently, most robotic therapies require therapists on-site, and limited techniques are available to support self-help post-stroke rehabilitation training.[13, 159] In this study, the feasibility and rehabilitation outcomes of a home-based self-help training assisted by EMG-driven WH-ENMS have been confirmed. The training setup used in the rehabilitation program and the system were easy to learn and easy to operate. All of the participants had received a pre-training tutorial and 3-session training at the laboratory before they could successfully conduct the home-based training with the prescribed training intensity and duration without any on-site professional supervision. There has been an exoskeleton robot (Myopro) developed for upper limb rehabilitation for self-help training at home for outpatients with stroke.[174] The participants had received at least 12 supervised sessions training with MyoPro (60 to 90 min per session) in the clinic to grasp device operation before the self-help training.[174] In the case of MyoPro, the rigid exoskeleton (1.8 kg, elbow–wrist–hand orthotic device) with nonnegligible weights mounted onto the paretic limb might cause incorrect alignment or migration during repeated practice.[13, 56] This additional safety concern pertaining to user-independent usage at home probably led a longer supervised training duration for the

patients to gain the competency required for independent use of the device.

In the present study, the training progress of the participants was telemonitored and found to be compliant with the prescribed training intensity. In the home-based training, the variation in the training among the participants ranged from 60 to 66 min per session. It is reported that training intensity and duration are important factors for clinical improvement.[148, 175] In a study on self-administered home-based training with a passive dynamic wrist-hand orthosis accompanied by gaming exercises,[176] participants were trained independently at home for six weeks and were recommended to practice for 30 min per day, six days per week. Limited motor improvement (i.e., no significant improvement in FMA) was found after the training. Besides the different effectiveness levels of the assistive devices, the inability to complete the recommended training duration was another key difficulties reported in that study.[176] A large amount of variation in training duration was observed among individuals, ranging from 2 to 60 min per day, because of lenient management and control of the training schedule (e.g., a lack of make-up sessions based on a quantitative and consistent protocol and delayed monitoring and follow-up in weeks rather than in days). Therefore, efficient monitoring of the training progress according to the prescribed rehabilitative protocol and schedule is important to ensure effective home-based self-help rehabilitation.

It also suggested that malfunctioning training systems in home-based rehabilitation should be easy to restore. Otherwise, unexpected drop-outs of recruited patients and violation of the training protocol could be encountered, as reported in a study on technology-supported home-based training.[177] In the present study, the technical problems were solved by directly replacing the malfunctioning systems efficiently with

backup systems without violating the training protocol, leading to effective rehabilitation and smooth user experience. Moreover, the availability of multiple duplications of the device required a low-cost design for home-based training systems. The compact design of the system could increase the feasibility of robot-assisted home-based training. Several existing home-based rehabilitation robots require a large physical space in the user's living environment,[150] which could be a challenge for patients living in crowded or small spaces.[155, 178] All of the participants in this study had adequate space in their house to accommodate the EMG-driven WH-ENMS due to the mobile and compact design of the system. Furthermore, the existing robotic devices are usually heavy and complex and require regular home visits for on-site installation, maintenance, and retrieval.[150] the case of the system used in the present study, the participants could bring the system back to the laboratory for replacement or return without the need for additional home visits by the experimental operator.

The system provides flexibility in terms of training schedule; for instance, a patient can choose to use it at weekends or even at midnight, which is not possible with traditional clinical services. It was found that the preferred training time slots selected by the participants were 14:00 to 16:00 and 19:00 to 21:00. However, in traditional out-patient rehabilitation, it is difficult to accommodate all patients in these time slots. This could be one of the reasons for the low compliance with and attendance of long-term service for outpatient rehabilitation after stroke.[179, 180] Furthermore, the home-based upper limb rehabilitation of four participants in this study was not stopped during the COVID-19 pandemic, but conventional face-to-face physiotherapy and occupational therapy have been largely suspended due to social distancing restrictions worldwide. The robotic technique and the associated home-based and self-help training mode in this study

provided an additional and effective option to the traditional rehabilitation to minimize the impact of physical distance control during the pandemic.

4.5 Periodic Summary

The results of this study suggested that the home-based self-help upper limb training assisted by the EMG-driven WH-ENMS was feasible and effective for improving upper limb function after stroke. After the training program, the participants exhibited significant motor improvement in the entire upper limb. Significant improvements were found in the voluntary motor control and muscle coordination of the upper limb, the increased smoothness and reduced compensatory trunk movement during arm reaching coordinated with distal movements, and the release of muscular spasticity at the elbow, wrist and fingers. This new training mode of home-based self-help telerehabilitation could be an additional and effective option to support regular and long-term rehabilitation for outpatients with stroke.

CHAPTER 5

CONCLUSIONS

Repeated-and-intensive upper limb training assisted by electromyography (EMG)-driven neuromuscular electrical stimulation (NMES)-robot hybrid system can be a promising approach for self-help and effective upper limb rehabilitation after stroke. In this study, three independent experiments were conducted to investigate the rehabilitation effectiveness of the EMG-driven NMES-robotic hand assisted upper limb training, evaluate the performance of a novel EMG-driven NMES-robot for self-help upper limb rehabilitation, and confirm the feasibility of using the developed system to assist home-based self-help upper limb training and its rehabilitation effectiveness.

In the first experiment, the rehabilitation effectiveness of EMG-driven NMES-robotic hand assisted upper limb training in participants with chronic stroke was investigated. Significant improvements in clinical scores ($P < 0.05$) and EMG parameters (including the muscle activation level and co-contraction index; $P < 0.05$) were found after the training. The results suggested that intensive and repetitive upper limb training with coordinated hand movements assisted by the EMG-driven NMES-robot facilitates hand function recovery and improves muscular coordination in the paretic upper limb with long sustainability in patients with chronic stroke.

In the second experiment, a novel EMG-driven exoneuromusculoskeleton was

developed for self-help upper limb training after stroke. The developed system, which combined the NMES, soft pneumatic muscle, and exoskeleton techniques, could assist the elbow, wrist, and fingers to perform sequential arm reaching and withdrawing tasks under voluntary effort control through EMG, had a lightweight, compact, and low power-requirement design. The designed musculoskeletons exerted sufficient mechanical torque to support joint extension for stroke survivors. Compared with no assistance was provided from the system, limb performance (measured as the range of motion in joint extension) was significantly improved when mechanical torque and NMES were provided ($P < 0.05$). All the participants completed the self-help device-assisted training with minimal professional assistance. Significantly improved voluntary motor function and significantly reduced muscle spasticity at the elbow, the wrist and the fingers were observed, as indicated by clinical scores ($P < 0.05$). EMG parameters ($P < 0.05$) indicated that the muscular coordination of the entire upper limb was significantly improved after the training. The results suggested that the developed system could support self-help upper limb training and facilitate effective motor recovery in patients with chronic stroke having severe-to-moderate upper limb impairments.

In the third experiment, the feasibility of a home-based self-help telerehabilitation program assisted by the EMG-driven wrist/hand exoneuromusculoskeleton (WH-ENMS) and its rehabilitation effects were investigated. All the participants could successfully conduct the home-based training with the prescribed training intensity and duration without any on-site professional supervision after they had received a pre-training tutorial and 3-session training at the laboratory. After the training program, motor function improvements were observed in all of the participants. The

improvements included the improved voluntary motor control and muscle coordination of the entire upper limb, increased smoothness and reduced compensatory trunk movement during arm reaching movements and object transportation, and reduction in muscular spasticity at the elbow, wrist and fingers. The results suggested that the home-based self-help telerehabilitation program assisted by EMG-driven WH-ENMS is feasible and effective for improving the motor function of the paretic upper limb after stroke.

In conclusion, the EMG-driven NMES-robot is recommended for use in assisting repeated-and-intensive training of the paralyzed upper limb with maximized voluntary motor effort and close-to-normal muscular coordination with minimized compensatory motions. Such training could effectively promote motor outcomes in both proximal and distal joints (including the elbow, wrist and fingers) in the paretic upper limb. In addition, this study presented a novel EMG-driven NMES-robot hybrid system, namely exoneuromusculoskeleton, for self-help and effective upper limb rehabilitation after stroke and a new self-help rehabilitation program for stroke survivors. The EMG-driven exoneuromusculoskeleton was found to be feasible to support self-help upper limb training in both laboratory and home settings. Moreover, significantly improved voluntary motor control and muscular coordination, and significantly reduced muscle spasticity of the paretic upper limb were achieved after the treatment. This new training mode could be an additional and effective option to support regular and long-term rehabilitation after stroke.

In the future work, further investigations will be conducted to (1) compare the rehabilitation effectiveness of EMG-driven EMNS-assisted upper limb training in

practical clinical service and in clinical trial with laboratory configuration for chronic stroke; (2) explore the training effectiveness of home-based self-help telerehabilitation assisted by EMG-driven EMNS in large scale, multi-center RCTs with long-term follow-up; (3) explore the training effectiveness of supplement training assisted by EMG-driven EMNS for early stroke rehabilitation; and (4) develop mobile upper limb training and evaluation system for self-help telerehabilitation.

APPENDICES

APPENDICES 1: CLINICAL ASSESSMENTS

1.1 Mini-Mental State Exam (MMSE)

Mini-Mental State Examination (MMSE)

Patient's Name: _____ Date: _____

***Instructions:* Ask the questions in the order listed. Score one point for each correct response within each question or activity.**

Maximum Score	Patient's Score	Questions
5		"What is the year? Season? Date? Day of the week? Month?"
5		"Where are we now: State? County? Town/city? Hospital? Floor?"
3		The examiner names three unrelated objects clearly and slowly, then asks the patient to name all three of them. The patient's response is used for scoring. The examiner repeats them until patient learns all of them, if possible. Number of trials: _____
5		"I would like you to count backward from 100 by sevens." (93, 86, 79, 72, 65, …) Stop after five answers. Alternative: "Spell WORLD backwards." (D-L-R-O-W)
3		"Earlier I told you the names of three things. Can you tell me what those were?"
2		Show the patient two simple objects, such as a wristwatch and a pencil, and ask the patient to name them.
1		"Repeat the phrase: 'No ifs, ands, or buts.'"
3		"Take the paper in your right hand, fold it in half, and put it on the floor." (The examiner gives the patient a piece of blank paper.)
1		"Please read this and do what it says." (Written instruction is "Close your eyes.")
1		"Make up and write a sentence about anything." (This sentence must contain a noun and a verb.)
1		"Please copy this picture." (The examiner gives the patient a blank piece of paper and asks him/her to draw the symbol below. All 10 angles must be present and two must intersect.) 
30		TOTAL

(Adapted from Rovner & Folstein, 1987)

Interpretation of the MMSE

Method	Score	Interpretation
Single Cutoff	<24	Abnormal
Range	<21	Increased odds of dementia
	>25	Decreased odds of dementia
Education	21	Abnormal for 8th grade education
	<23	Abnormal for high school education
	<24	Abnormal for college education
Severity	24-30	No cognitive impairment
	18-23	Mild cognitive impairment
	0-17	Severe cognitive impairment

Sources:

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https://pdfs.semanticscholar.org/4370/72f1421146674eaf98e11cc9079311f23fcb.pdf

1.2 Fugl-Meyer Assessment for Upper Extremity

FMA-UE PROTOCOL — Rehabilitation Medicine, University of Gothenburg

FUGL-MEYER ASSESSMENT **ID:**
UPPER EXTREMITY (FMA-UE) **Date:**
Assessment of sensorimotor function **Examiner:**

Fugl-Meyer AR, Jaasko L, Leyman I, Olsson S, Steglind S: The post-stroke hemiplegic patient. A method for evaluation of physical performance. Scand J Rehabil Med 1975, 7:13-31.

A. UPPER EXTREMITY, sitting position					
I. Reflex activity				**none**	**can be elicited**
Flexors: biceps and finger flexors (at least one) **Extensors**: triceps				0 0	2 2
			Subtotal I (max 4)		
II. Volitional movement within synergies, without gravitational help				**none**	**partial**	**full**
Flexor synergy: Hand from contralateral knee to ipsilateral ear. From extensor synergy (shoulder adduction/ internal rotation, elbow extension, forearm pronation) to flexor synergy (shoulder abduction/ external rotation, elbow flexion, forearm supination). **Extensor synergy:** Hand from ipsilateral ear to the contralateral knee	Shoulder	retraction		0	1	2
		elevation		0	1	2
		abduction (90°)		0	1	2
		external rotation		0	1	2
	Elbow	flexion		0	1	2
	Forearm	supination		0	1	2
	Shoulder	adduction/internal rotation		0	1	2
	Elbow	extension		0	1	2
	Forearm	pronation		0	1	2
			Subtotal II (max 18)			
III. Volitional movement mixing synergies, without compensation				**none**	**partial**	**full**
Hand to lumbar spine hand on lap	cannot perform or hand in front of ant-sup iliac spine hand behind ant-sup iliac spine (without compensation) hand to lumbar spine (without compensation)			0	1	2
Shoulder flexion 0°- 90° elbow at 0° pronation-supination 0°	immediate abduction or elbow flexion abduction or elbow flexion during movement flexion 90°, no shoulder abduction or elbow flexion			0	1	2
Pronation-supination elbow at 90° shoulder at 0°	no pronation/supination, starting position impossible limited pronation/supination, maintains starting position full pronation/supination, maintains starting position			0	1	2
			Subtotal III (max 6)			
IV. Volitional movement with little or no synergy				**none**	**partial**	**full**
Shoulder abduction 0 - 90° elbow at 0° forearm pronated	immediate supination or elbow flexion supination or elbow flexion during movement abduction 90°, maintains extension and pronation			0	1	2
Shoulder flexion 90° - 180° elbow at 0° pronation-supination 0°	immediate abduction or elbow flexion abduction or elbow flexion during movement flexion 180°, no shoulder abduction or elbow flexion			0	1	2
Pronation/supination elbow at 0° shoulder at 30°- 90° flexion	no pronation/supination, starting position impossible limited pronation/supination, maintains start position full pronation/supination, maintains starting position			0	1	2
			Subtotal IV (max 6)			
V. Normal reflex activity assessed only if full score of 6 points is achieved in part IV; compare with the unaffected side				**0 (IV), hyper**	**lively**	**normal**
biceps, triceps, finger flexors	2 of 3 reflexes markedly hyperactive or 0 points in part IV 1 reflex markedly hyperactive or at least 2 reflexes lively maximum of 1 reflex lively, none hyperactive			0	1	2
			Subtotal V (max 2)			
			Total A (max 36)			

Approved by Fugl-Meyer AR 2010 1 Updated 2015-03-11

B. WRIST support may be provided at the elbow to take or hold the starting position, no support at wrist, check the passive range of motion prior testing		none	partial	full
Stability at 15° dorsiflexion elbow at 90°, forearm pronated shoulder at 0°	less than 15° active dorsiflexion dorsiflexion 15°, no resistance tolerated maintains dorsiflexion against resistance	0	1	2
Repeated dorsifexion / volar flexion elbow at 90°, forearm pronated shoulder at 0°, slight finger flexion	cannot perform volitionally limited active range of motion full active range of motion, smoothly	0	1	2
Stability at 15° dorsiflexion elbow at 0°, forearm pronated slight shoulder flexion/abduction	less than 15° active dorsiflexion dorsiflexion 15°, no resistance tolerated maintains dorsiflexion against resistance	0	1	2
Repeated dorsifexion / volar flexion elbow at 0°, forearm pronated slight shoulder flexion/abduction	cannot perform volitionally limited active range of motion full active range of motion, smoothly	0	1	2
Circumduction elbow at 90°, forearm pronated shoulder at 0°	cannot perform volitionally jerky movement or incomplete complete and smooth circumduction	0	1	2
	Total B (max 10)			

C. HAND support may be provided at the elbow to keep 90° flexion, no support at the wrist, compare with unaffected hand, the objects are interposed, active grasp		none	partial	full
Mass flexion from full active or passive extension		0	1	2
Mass extension from full active or passive flexion		0	1	2
GRASP				
a. Hook grasp flexion in PIP and DIP (digits II-V), extension in MCP II-V	cannot be performed can hold position but weak maintains position against resistance	0	1	2
b. Thumb adduction 1-st CMC, MCP, IP at 0°, scrap of paper between thumb and 2-nd MCP joint	cannot be performed can hold paper but not against tug can hold paper against a tug	0	1	2
c. Pincer grasp, opposition pulpa of the thumb against the pulpa of 2-nd finger, pencil, tug upward	cannot be performed can hold pencil but not against tug can hold pencil against a tug	0	1	2
d. Cylinder grasp cylinder shaped object (small can) tug upward, opposition of thumb and fingers	cannot be performed can hold cylinder but not against tug can hold cylinder against a tug	0	1	2
e. Spherical grasp fingers in abduction/flexion, thumb opposed, tennis ball, tug away	cannot be performed can hold ball but not against tug can hold ball against a tug	0	1	2
	Total C (max 14)			

D. COORDINATION/SPEED, sitting, after one trial with both arms, eyes closed, tip of the index finger from knee to nose, 5 times as fast as possible		marked	slight	none
Tremor	at least 1 completed movement	0	1	2
Dysmetria at least 1 completed movement	pronounced or unsystematic slight and systematic no dysmetria	0	1	2
		≥ 6s	**2 - 5s**	**< 2s**
Time start and end with the hand on the knee	at least 6 seconds slower than unaffected side 2-5 seconds slower than unaffected side less than 2 seconds difference	0	1	2
	Total D (max 6)			

TOTAL A-D (max 66)	

H. SENSATION, upper extremity eyes closed, compared with the unaffected side		**anesthesia**	**hypoesthesia or dysesthesia**	**normal**
Light touch	upper arm, forearm palmary surface of the hand	0 0	1 1	2 2
		less than 3/4 correct or absence	**3/4 correct or considerable difference**	**correct 100%, little or no difference**
Position small alterations in the position	shoulder elbow wrist thumb (IP-joint)	0 0 0 0	1 1 1 1	2 2 2 2
			Total H (max12)	

J. PASSIVE JOINT MOTION, upper extremity, sitting position, compare with the unaffected side				**J. JOINT PAIN** during passive motion, upper extremity		
	only few degrees (less than 10° in shoulder)	decreased	normal	pronounced pain during movement or very marked pain at the end of the movement	some pain	no pain
Shoulder						
Flexion (0° - 180°)	0	1	2	0	1	2
Abduction (0°-90°)	0	1	2	0	1	2
External rotation	0	1	2	0	1	2
Internal rotation	0	1	2	0	1	2
Elbow						
Flexion	0	1	2	0	1	2
Extension	0	1	2	0	1	2
Forearm						
Pronation	0	1	2	0	1	2
Supination	0	1	2	0	1	2
Wrist						
Flexion	0	1	2	0	1	2
Extension	0	1	2	0	1	2
Fingers						
Flexion	0	1	2	0	1	2
Extension	0	1	2	0	1	2
Total (max 24)				**Total** (max 24)		

A. UPPER EXTREMITY	/36
B. WRIST	/10
C. HAND	/14
D. COORDINATION / SPEED	/ 6
TOTAL A-D (motor function)	/66

H. SENSATION	/12
J. PASSIVE JOINT MOTION	/24
J. JOINT PAIN	/24

https://neurophys.gu.se/digitalAssets/1520/1520773_fma-ue-protocol-english-updated-20150315.pdf

1.3 Action Research Arm Test

ACTION RESEARCH ARM TEST

Patient Name: _____
Rater Name: _____
Date: _____

Instructions
There are four subtests: Grasp, Grip, Pinch, Gross Movement. Items in each are ordered so that:

- if the subject passes the first, no more need to be administered and he scores top marks for that subtest;
- if the subject fails the first *and* fails the second, he scores zero, and again no more tests need to be performed in that subtest;
- otherwise he needs to complete all tasks within the subtest

Activity	Score
Grasp	
1. Block, wood, 10 cm cube (If score = 3, total = 18 and to Grip) Pick up a 10 cm block	_____
2. Block, wood, 2.5 cm cube (If score = 0, total = 0 and go to Grip) Pick up 2.5 cm block	_____
3. Block, wood, 5 cm cube	_____
4. Block, wood, 7.5 cm cube	_____
5. Ball (Cricket), 7.5 cm diameter	_____
6. Stone 10 x 2.5 x 1 cm	_____
Coefficient of reproducibility = 0.98	
Coefficient of scalability = 0.94	
Grip	
1. Pour water from glass to glass (If score = 3, total = 12, and go to Pinch)	_____
2. Tube 2.25 cm (If score = 0, total = 0 and go to Pinch)	_____
3. Tube 1 x 16 cm	_____
4. Washer (3.5 cm diameter) over bolt	_____
Coefficient of reproducibility = 0.99	
Coefficient of scalability = 0.98	
Pinch	
1. Ball bearing, 6 mm, 3rd finger and thumb (If score = 3, total = 18 and go to Grossmt)	_____
2. Marble, 1.5 cm, index finger and thumb (If score = 0, total = 0 and go to Grossmt)	_____
3. Ball bearing 2nd finger and thumb	_____
4. Ball bearing 1st finger and thumb	_____
5. Marble 3rd finger and thumb	_____
6. Marble 2nd finger and thumb	_____
Coefficient of reproducibility = 0.99	
Coefficient of scalability = 0.98	

Provided by the Internet Stroke Center — www.strokecenter.org

Grossmt (Gross Movement)

1. Place hand behind head (If score = 3, total = 9 and finish) _____
2. (If score = 0, total = 0 and finish _____
3. Place hand on top of head _____
4. Hand to mouth _____

Coefficient of reproducibility = 0.98

Coefficient of scalability = 0.97

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1.4 Functional Independent Measurement

Functional Independence Measure (FIM)

LEVELS		
	4- Complete Independence (Timely, Safely) 3- Incomplete Independence (Device)	NO HELPER
	2- Incomplete Dependence (A. Supervision B. Minimal C. Moderate Assist) 1- Complete Dependence (Maximal Assist: Helper > Subject)	HELPER

	ADMIT	DISCH	FOL-UP
Self Care			
A. Eating			
B. Grooming			
C. Bathing			
D. Dressing-Upper Body			
E. Dressing-Lower Body			
F. Perineal Care			
Sphincter Control			
G. Bladder Management			
H. Bowel Management			
Mobility			
Transfer:			
I. Bed, Chair, W/Chair			
J. Toilet			
K. Tub, Shower			
Locomotion			
L. Walking			
M. Wheelchair			
N. Stairs			
Communication			
O. Comprehension			
P. Expression			
Social Adjustment			
Q. Cooperation			
Cognition			
R. Problem Solving			

Modified Ashworth Scale

Modified Ashworth Scale Instructions

General Information (derived Bohannon and Smith, 1987):

- Place the patient in a supine position
- If testing a muscle that primarily flexes a joint, place the joint in a maximally flexed position and move to a position of maximal extension over one second (count "one thousand one")
- If testing a muscle that primarily extends a joint, place the joint in a maximally extended position and move to a position of maximal flexion over one second (count "one thousand one")
- Score based on the classification below

Scoring (taken from Bohannon and Smith, 1987):

0	No increase in muscle tone
1	Slight increase in muscle tone, manifested by a catch and release or by minimal resistance at the end of the range of motion when the affected part(s) is moved in flexion or extension
1+	Slight increase in muscle tone, manifested by a catch, followed by minimal resistance throughout the remainder (less than half) of the ROM
2	More marked increase in muscle tone through most of the ROM, but affected part(s) easily moved
3	Considerable increase in muscle tone, passive movement difficult
4	Affected part(s) rigid in flexion or extension

Patient Instructions:
The patient should be instructed to relax.

https://www.sralab.org/sites/default/files/2017-06/Modified%20Ashworth%20Scale%20Instructions.pdf

APPENDICES 2: CONSENT FORM

2.1 Consent form for Chapter 2

Consent form

I, _____ (name of subject), hereby consent to participate as a subject for the project entitled "Intention-Driven Neuromuscular Electrical Stimulation (NMES) Robotic Hand Assisted Upper Limb Rehabilitation After Stroke".

- I have understood the experimental procedures presented to me.
- I have given an opportunity to ask questions about the experiment, and these have been answered to my satisfaction.
- I have understood the information presented in the information sheet.
- I realize the experiment will possibly benefit my upper limb motor functions.
- The testing should not result in any undue discomfort, I realize that I can discontinue the experiment with no reasons given and no penalty received during the experiment.
- I realize that the results of this experiment may be published, but that my own results will be kept confidential.
- I realize that the results of this experiment are the properties of The Hong Kong Polytechnic University.
- I agree that the PI and the project research members, who obtained the authorization from the PI, can use my experimental data for this project study.

Subject name: _____ Signature: _____ Date: _____

Witness: _____ Signature: _____ Date: _____

Investigator:_____ Signature: _____ Date: _____

同意書

我，_____(受試者姓名)，在此同意作為受試者參加 "神經肌肉電刺激機械系統上肢訓練"。

- 我已明白到該測試的步驟。
- 我已給予機會詢問有關該測試的問題，並已獲得滿意的回答。
- 我已明白在資料單張上所寫的所有內容
- 我已明白這個實驗有可能可以改善我的上肢運動功能
- 此實驗不會給您帶來不適，我已明白在實驗中我可以終止測試而無需給予任何理由，或由此而受到任何懲罰。
- 我已知道這個測試的結果可被發表，但有關我個人的結果將獲得保密。
- 我已知道這個測試的結果屬香港理工大學。
- 我同意本項目負責人及其受權的項目研究人員使用我的實驗記錄以作此項目的研究。

受試者姓名_____ 簽署_____日期_____

作證人姓名_____ 簽署_____日期_____

研究員姓名_____ 簽署_____日期_____

2.2 Consent form for Chapter 3 and 4

Consent form

I, _____ (name of subject), hereby consent to participate as a subject for the project entitled "Exoneuromusculoskeleton System for Mobile Rehabilitation on the Upper Limb".

- I have understood the experimental procedures presented to me.
- I have given an opportunity to ask questions about the experiment, and these have been answered to my satisfaction.
- I have understood the information presented in the information sheet.
- I realize the experiment will possibly benefit my upper limb motor functions.
- The testing should not result in any undue discomfort, I realize that I can discontinue the experiment with no reasons given and no penalty received during the experiment.
- I realize that the results of this experiment may be published, but that my own results will be kept confidential.
- I realize that the results of this experiment are the properties of The Hong Kong Polytechnic University.
- I agree that the PI and the project research members, who obtained the authorization from the PI, can use my experimental data for this project study.

Subject name: _____ Signature: _____ Date: _____

Witness: _____ Signature: _____ Date: _____

Investigator:_____ Signature: _____ Date: _____

同意書

我，_____(受試者姓名), 在此同意作為受試者參加 "外神經肌骨康復系統上肢訓練"。

- 我已明白到該測試的步驟。
- 我已給予機會詢問有關該測試的問題, 並已獲得滿意的回答。
- 我已明白在資料單張上所寫的所有內容
- 我已明白這個實驗有可能可以改善我的上肢運動功能
- 此實驗不會給您帶來不適, 我已明白在實驗中我可以終止測試而無需給予任何理由, 或由此而受到任何懲罰。
- 我已知道這個測試的結果可被發表, 但有關我個人的結果將獲得保密。
- 我已知道這個測試的結果屬香港理工大學。
- 我同意本項目負責人及其受權的項目研究人員使用我的實驗記錄以作此項目的研究。

受試者姓名_____ 簽署_____日期_____

作證人姓名_____ 簽署_____日期_____

研究員姓名_____ 簽署_____日期_____

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