EXONEUROMUSCULOSKELETON-ASSISTED TELEREHABILITATION FOR MOTOR RECOVERY IN STROKE SURVIVORS

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Exoneuromusculoskeleton-Assisted Telerehabilitation for Motor Recovery in Stroke Survivors

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CERTIFICATE OF ORIGINALITY

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ABSTRACT

Stroke is a growing global health challenge that results in profound and lasting motor disability. Conventional rehabilitation falls short of providing stroke survivors, once discharged, with the high-intensity and long-term therapy necessary to address residual impairments. Telerehabilitation has emerged to bridge this service gap, and robot-assisted training (RAT) offers a promising way to deliver repetitive, intensive, and physically assisted therapy in home environments. However, the real-world effectiveness of RAT when deployed outside highly controlled research environments, such as clinical practice and home-based settings, remains poorly understood. Moreover, evidence for the durability and generalization of RAT-induced functional gains is limited.

Therefore, this study had three main objectives: (i) to develop a telerehabilitation framework that integrates Internet of Things (IoT) and ankle-foot exoneuromusculoskeleton (AF-ENMS) to facilitate home-based robot-assisted gait training (RAGT); (ii) to investigate the feasibility of translating a wrist/hand exoneuromusculoskeleton (WH-ENMS)-assisted telerehabilitation program from a controlled laboratory setting into routine clinical service, and to compare differences in logistical management and rehabilitative outcomes; (iii) to evaluate the long-term rehabilitation effects of the WH-ENMS-assisted telerehabilitation program in clinical service.

The first section developed an Internet of ENMS framework by integrating IoT technology with AF-ENMS to enable remote therapist supervision, cyber interaction among stroke users, and digital management of training progress. Individuals with chronic stroke (n = 16) participated in a validation trial consisting of 20 sessions of RAGT in home environments. The results confirmed the feasibility of the system, with high patient engagement, smooth management, and positive user satisfaction. Significant improvements in lower limb motor function and gait patterns were observed after the training, and at three months after the training.

The second section investigated the clinical translation of a telerehabilitation program assisted by WH-ENMS for upper-limb recovery. Stroke patients received a 20-session telerehabilitation program either in the lab (n = 12) or the clinic (n = 12) settings. Variations in the arrangement of trial implementation were observed. The results demonstrated that the integration of robot-assisted telerehabilitation into clinical service was feasible and effective. However, functional gains in the clinic group were reduced compared with the lab group, possibly due to adoption of more compensatory strategies and less qualified patient-operator interactions.

The third section evaluated the long-term effects of a WH-ENMS-assisted telerehabilitation program in clinic service. Participants with chronic stroke (n = 20) completed a 20-session telerehabilitation program, with outcomes measured at baseline, post-intervention, and at three- and six-month follow-ups. The results demonstrated

sustained improvements in upper limb motor function, achieved primarily through reductions in muscular compensation and improvements in voluntary coordination.

In conclusion, this study developed and validated a novel framework for robot-assisted telerehabilitation and tele-management, advancing understanding of patient needs and safety considerations during unsupervised home-based RAGT. Additionally, this study illustrated the feasibility of translating a robot-assisted telerehabilitation program into clinical service, highlighting logistical variations in therapeutic benefit. Finally, long-term outcomes from clinic-based telerehabilitation provide important insights into the sustained functional benefits of RAT and its potential for real-world deployment in telerehabilitation.

LIST OF RESEARCH OUTPUT

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(1) **Qing, W.**; Nam, C.-Y.; Shum, H.M.-H.; Chan, M.K.-L.; Yu, K.-P.; Ng, S.S.-W.; Yang, B.; Hu, X. Long-Term Effects of Mobile Exoneuromusculoskeleton (ENMS)-Assisted Self-Help Telerehabilitation after Stroke. *Frontiers in Neuroscience* **2024**, 18.

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(6) Lin, L.; **Qing, W.**; Huang, Y.; Ye, F.; Rong, W.; Li, W.; Jiao, J.; Hu, X. Comparison of Immediate Neuromodulatory Effects between Focal Vibratory and Electrical Sensory Stimulations after Stroke. *Bioengineering (Basel)* **2024**, 11, 286.

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(2) **Qing, W.**; Song, H.; Lin, L.; Ye, F.; Hu, X. Effects of Exoneuromusculoskeleton-Assisted Lower Limb Telerehabilitation on Poststroke Muscular Compensation, *11th World Association for Chinese Biomedical Engineers (WACBE) World Congress on Bioengineering*, **2024**, Hong Kong, China.

(3) **Qing, W.**; Song, H.; Lin, L.; Ye, F.; Hu, X. Self-Help Cyber-Paired Telerehabilitation Assisted by an Ankle-Foot Exoneuromusculoskeleton for

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(4) Hu, X.; Nam, C.; Ye, F.; **Qing, W.**; Miao, J. Mobile Exoneuromusculoskeletons (ENMSs): Neuromuscular Electrical Stimulation (NMES) and Soft Robot Hybrid Systems for Personalized Telerehabilitation Poststroke. *In Proceedings of the Converging Clinical and Engineering Research on Neurorehabilitation V*, **2024**; pp. 530-533.

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(6) **Qing, W.**; Song, H.; Lin, L.; Ye, F.; Hu, X. Reorganization of Undirected and Directed Cortico-Muscular Connectivity After Exoneuromusculoskeleton-Assisted Telerehabilitation. *In Proceedings of the 17th International Convention on Rehabilitation Engineering and Assistive Technology (i-CREATe)*, **2024**; pp. 1-5.

(7) Lin, L.; Kuet, M.T.; **Qing, W.**; Zhao, H.; Ye, F.; Huang, Y.; Hu, X. Effects of Sensorimotor-Integrated (SMI) Wrist/Hand Rehabilitation Assisted by a Hybrid

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LIST OF ABBREVIATIONS

ADL	Activity of Daily Living
AF-ENMS	Ankle-Foot Exoneuromusculoskeleton
ANCOVA	Analysis of Covariance
ANOVA	Analysis of Variance
APB	Abductor Pollicis Brevis
App	Application
ARAT	Action Research Arm Test
BBS	Berg Balance Scale
BF	Biceps Femoris
BIC	Biceps Brachii
CE	Clinical Engineer
CI	Co-contraction Index
CL	Confidence Level
CONSORT	Consolidated Standards of Reporting Trials
CRSSC	Community Rehabilitation Service Support Centre
ECU	Extensor Carpi Ulnaris
ED	Extensor Digitorum
EMG	Electromyography

ENMS	Exoneuromusculoskeleton
FAC	Functional Ambulatory Category
FCR	Flexor Carpi Radialis
FD	Flexor Digitorum
FIM	Functional Independence Measure
FMA-LE	Fugl-Meyer Assessment for Lower Extremity
FMA-UE	Fugl-Meyer Assessment for Upper Extremity
FSR	Force Sensitive Resistor
GL	Lateral Gastrocnemius
IMI	Intrinsic Motivation Inventory
Io-ENMS	Internet of Exoneuromusculoskeleton
IoT	Internet of Things
LF	Lateral Forefoot
LLM	Large Language Model
LM	Lateral Midfoot
LR	Lateral Rearfoot
MAS	Modified Ashworth Scale
MF	Medial Forefoot
MM	Medial Midfoot

MMSE	Mini-Mental State Examination
MR	Medial Rearfoot
MTD	Maximal Trunk Displacement
MVC	Maximal Voluntary Contraction
NMES	Neuromuscular Electrical Stimulation
NMU	Number of Movement Units
OT	Occupational Therapist
OTA	Occupational Therapy Assistant
PT	Physical Therapist
RAGT	Robot-Assisted Gait Training
RAT	Robot-Assisted Training
RCT	Randomized Controlled Trial
SD	Standard Deviation
SE	Standard Error
TA	Tibialis Anterior
TRI	Triceps Brachii
USE	Usefulness, Satisfaction, and Ease of Use
VME	Voluntary Motor Effort
VMO	Vastus Medialis Oblique

VR	Virtual Reality
WH-ENMS	Wrist-Hand Module of The Exoneuromusculoskeleton
WMFT	Wolf Motor Function Test
3D	Three-Dimensional
3MFU	3-Month Follow-up
6MFU	6-Month Follow-up
10MWT	10 Meter Walk Test

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CHAPTER 1

INTRODUCTION

1.1 Stroke population and situation

1.1.1 Overview of stroke population

Stroke is the main cause of long-term disability worldwide [1]. The Global Burden of Disease 2021 estimates paint a stark picture: globally, one in four adults over 25 will experience a stroke at some point in their lives [2]. In 2021 alone, it is estimated that there were 93.8 million prevalent strokes and 11.9 million new (incident) strokes, with over 100 million people worldwide having experienced a stroke [2]. While age-standardized incidence and mortality rates have shown a decline in high-income countries because of better prevention and acute care, the absolute number of affected individuals continues to climb, driven by population growth, aging, and a shifting risk factor profile [3]. Mirroring global trends, stroke is a major cause of morbidity in Hong Kong [4]. The Population Health Survey 2020-22 revealed that 0.8% of individuals aged 15 or above reported a doctor-diagnosed stroke, with prevalence increasing sharply with age [5]. There is a 52% increase in people living with stroke, rising from 37,800 in 2009/10 to 57,500 in 2018/19 [6, 7]. A particularly concerning trend in Hong Kong is the rising incidence of young stroke in those aged 18 to 55. This trend is linked to the high prevalence of modifiable risk factors in the local population, such as

hypertension, high cholesterol, and excessive salt intake [8]. This demographic shift means that an increasing proportion of stroke survivors are of working age, often serving as their family's primary breadwinners, which magnifies the socioeconomic consequences of the disease.

From these data, advances in acute stroke care have improved survival rates; however, survival does not equate to full recovery. A large and growing proportion of survivors are left with chronic, life-altering disabilities. This, combined with the rising incidence in younger populations, has placed an unprecedented and escalating strain on healthcare systems, economies, and families worldwide.

1.1.2 Motor impairments after stroke

Motor dysfunction represents the most prevalent neurological impairment after stroke, exerting a profound impact on overall quality of life [9]. Poststroke motor impairments typically involve the upper and lower extremities contralateral to the brain lesion, and manifest as a combination of negative signs, representing a loss of normal function, and positive signs, the emergence of abnormal phenomena [10]. Approximately 85% of stroke survivors obtain some degree of upper limb impairment [11], and approximately 50% of these patients suffer from impaired upper limb function in the long run [12]. Lower limb impairments are also prevalent, affecting around 72% of patients [13]. While regaining independent walking is the most common rehabilitation goal, current standard care leaves about 50% of stroke survivors with impaired walking ability at the

chronic stage [14]. In addition, a key challenge in motor recovery is the disparity between proximal and distal limb recovery. Recovery of movements involving small, distal joints (e.g., wrist, hand, ankle, and foot) is often more challenging and slower compared to those of larger, more proximal joints. This disparity is partly attributed to the natural poststroke trajectory of motor restitution, which generally follows a proximal-to-distal sequence, and partly to the limitations of conventional therapist-guided interventions in simultaneously addressing the fine, coordinated movements required for distal control [15]. Consequently, the limited recovery of fine motor skills constitutes a major barrier to regaining independence in activities of daily living (ADLs), such as eating, dressing, and near-normal walking.

1.1.3 Neurorehabilitation after stroke

Post-stroke neurorehabilitation is essentially a motor re-education process aimed at regaining impaired limb function [16]. This recovery is fundamentally driven by neuroplasticity, i.e., the brain's ability to reorganize itself [17]. The central goal of neurorehabilitation is therefore to promote beneficial neuroplasticity while mitigating maladaptive changes [18]. To achieve this, rehabilitation must be delivered in a structured and evidence-based manner. High doses of intensive, repetitive training are essential, as motor learning and neuroplasticity are use-dependent, which means that the extent of reorganization of the brain is directly proportional to the amount of practice. Evidence from motor learning demonstrates that thousands of repetitions are

often required to re-establish motor skills [19]. Another important principle is task specificity. The brain learns what it practices, so engaging in functional, goal-oriented tasks (e.g., reaching for a cup, manipulating an object) is more effective than performing isolated or generic movements, as they strengthen neural circuits that are directly relevant to real-world activities [19]. Effective neurorehabilitation should also discourage reliance on compensatory habits, which patients often adopt early in recovery by using their less-affected limbs or inefficient patterns. While these strategies allow for immediate task completion, they can reinforce maladaptive plasticity and inhibit the recovery of the paretic limb [20]. To counter this, assistance provided intelligently and in synchrony with voluntary effort can minimize compensatory movements. Passive limb movement risks reinforcing spasticity, since a machine cannot distinguish between voluntary motor commands and involuntary reflexes. By contrast, well-timed assistance that amplifies the patient's voluntary motor output strengthens the correct neural pathways while avoiding maladaptive reinforcement. Taken together, rehabilitation strategies that emphasize intensive, repetitive use of the paretic limb, while promoting maximal voluntary motor effort (VME) and reducing compensatory movements to approximate normal muscle coordination, are essential for poststroke functional recovery.

1.1.4 Difficulties in long-term rehabilitation service

Despite strong evidence that neuroplasticity-driven recovery requires intensive,

repetitive, and long-term training, stroke survivors often face significant barriers to accessing adequate rehabilitation. There is a fundamental mismatch between the biology demands of poststroke recovery and the logistics of healthcare systems. As described above, neuroplastic change demands a high dosage of therapy—thousands of repetitions delivered consistently over months or even years—to drive meaningful functional gains [21]. However, the conventional healthcare model is structured for episodic, time-limited, and geographically constrained care, causing a dosage gap that significantly impedes optimal recovery. The most apparent dosage gap occurs after patients are discharged from inpatient care [22], a phenomenon that we refer to here as the "rehabilitation cliff". After discharge, many stroke survivors, particularly those in remote or underserved areas, face significant barriers to accessing qualified rehabilitation professionals and specialized equipment due to limited therapist availability and logistical challenges such as transportation. As a result, formal therapy often ends prematurely, leaving patients to manage persistent impairments with fragmented support or inconsistent support [23]. Many patients and caregivers report a profound lack of continuity of care and express a strong desire for ongoing opportunities to practice and keep the door open for recovery [22]. Therefore, there is an urgent need to bridge the "rehabilitation cliff" with long-term, accessible, and effective rehabilitation services.

1.2 Telerehabilitation for motor function after stroke

In response to systemic barriers limiting access to conventional care, the field of neurorehabilitation has increasingly adopted technological solutions to bridge the "rehabilitation cliff". Telerehabilitation, the delivery of rehabilitation interventions through information and communication technologies, has gained recognition as a viable approach for expanding access to care and supporting sustained motor recovery across geographical barriers and during global health crises such as COVID-19 [24, 25].

1.2.1 Current methods for stroke telerehabilitation

Telerehabilitation can be delivered through two primary models, synchronous and asynchronous. The synchronous model enables real-time communication between patients and therapists, typically via videoconferencing, providing direct supervision, feedback, and education. Videoconferencing-based intervention has been reported to be as effective as traditional in-person therapy in improving functional performance and is generally well accepted by stroke survivors [26]. However, its major limitation lies in the substantial time commitment from healthcare professionals. Furthermore, the absence of physical interaction prevents therapists from delivering hands-on assistance, tactile cues, or direct guidance, which are critical elements for stroke patients with moderate-to-severe motor impairments to minimize compensatory movements. On the other hand, the asynchronous model allows patients to access pre-recorded materials or use interactive systems at their convenience, with a therapist monitoring their progress

offline [27]. Virtual Reality (VR) is a key technology incorporated in this model to enhance engagement and interactivity. By immersing users in environments with multiple senses and simulations, VR can provide real-time feedback and encourage high-repetition, task-specific training through gamification. Evidence suggests that VR, especially when used as an adjunct to conventional therapy, can result in significant enhancements to motor function [28]. Other technologies, such as mobile applications (Apps) and wearable sensors [29], have been used for asynchronous telerehabilitation. Smartphone- or tablet-based Apps allow stroke patients to access prescribed exercises on demand and perform exercises without supervision. When integrated with wearable sensors, their movement metrics and performance data can be tracked and transmitted to therapists for remote monitoring. Despite these asynchronous approaches supporting flexible or immersed, home-based therapy, they fail to deliver the direct physical guidance required for patients to relearn specific motor patterns, thereby constraining the overall therapeutic effectiveness.

1.2.2 Robot-assisted telerehabilitation

Robot-assisted training (RAT) represents a technological leap for stroke rehabilitation, introducing the capacity for direct physical interaction with the patient, increased support for patients with severe impairments, and extensive data collection. Robotic systems, which range from end-effector devices to full exoskeletons, deliver highly intensive and repetitive training, providing consistent, high-dosage therapy over

extended periods, which is difficult for human therapists to replicate. By physically assisting limb movements, robots can minimize compensatory strategies, which are invaluable for stroke patients who lack sufficient strength to initiate movement independently. In addition, these systems offer precise, objective data on performance metrics such as force, velocity, and range of motion, facilitating accurate and continuous monitoring of patient progress.

Despite decades of development and evidence supporting its clinical benefits, the widespread adoption of RAT has been limited. The primary barrier is that most rehabilitation robots remain large, heavy, complex, and prohibitively expensive, confining their use to well-funded clinics and research laboratories [30]. Recent advances in more portable and user-friendly devices, such as robotic gloves for hand and wrist rehabilitation [31, 32], have made RAT more suitable for home-based telerehabilitation. Nonetheless, several challenges remain, including unverified usability, as many robotic systems require a certain level of technical proficiency for setup, calibration, and troubleshooting. This can be burdensome for stroke survivors and their caregivers, who were reported to lack the necessary skills or confidence to manage the technology independently [33]. Safety concerns with unsupervised home use are also significant, particularly the risk of falls during robot-assisted gait training (RAGT). Additionally, without professional supervision, patients may adopt incorrect or compensatory movement patterns, potentially reinforcing maladaptive motor

strategies and undermining their recovery. These challenges highlight that successful home-based RAT requires more than user-friendly robots. It necessitates the development and validation of robot-assisted telerehabilitation systems and programs that ensure training safety, maximize therapeutic effectiveness, and minimize cognitive and technical burdens on end users.

1.2.3 Management of telerehabilitation

Managing home-based telerehabilitation is crucial for ensuring adherence and therapeutic efficacy, especially given the inherent complexities and potential safety concerns of RAT. Unfortunately, management strategies have been ignored in most telerehabilitation studies, relying solely on basic communication methods such as telephone calls and text messages. Leveraging modern information and technology infrastructure, telerehabilitation management can be developed further to maintain post-discharge care continuity and long-term motor recovery.

When translating rehabilitation protocols to home environments, a key difference is the reduced level of direct, real-time supervision compared to in-person therapy, where an operator can physically spot, correct form, and ensure proper execution. This limitation underscores the need for effective monitoring systems within telerehabilitation programs. Advances in the Internet of Things (IoT) provide a solid technological foundation for this. IoT-based architectures support continuous acquisition of training data from on-body or robotic sensors, with secure transmission to cloud repositories for

longitudinal performance tracking and analysis [34]. This data-driven approach provides healthcare professionals with objective insights into patient progress, allowing them to identify abnormal movements, detect non-adherence to prescribed protocols, and adjust therapeutic parameters remotely. Paired with communication and support channels, therapists can provide clinical feedback and maintain a therapeutic alliance remotely to support patient training. Early studies have explored IoT-driven telerehabilitation frameworks; however, most of them were designed to support long-term upper limb training [35], and evidence regarding their effects on patient engagement and motor outcome remains inconsistent [36], underscoring the need for further refinement and clinical validation.

Furthermore, telerehabilitation inherently reduces direct human contact and peer interaction compared to traditional clinical settings. In the clinic, patients often benefit from the presence of therapists and peers, gaining encouragement, shared experiences, all of which contribute to long-term adherence and psychological well-being [37]. In contrast, individual home-based rehabilitation typically lacks these social elements, making it challenging to replicate the motivational cues and interpersonal support provided by in-person therapy. In this case, integrating social support into telerehabilitation may help address this limitation by enhancing engagement and motivation during stroke recovery. For example, one study found that social support from healthcare providers and peers could improve stroke patients' motivation and

quality of life [38], and stroke peer visits have been reported to provide emotional encouragement and reduce feelings of isolation [39]. Building on these findings, cyber-paired training models, where multiple patients are paired and trained under therapist supervision, could create a "minimal community" that restores aspects of social support.

In conclusion, future developments and implementations of telerehabilitation systems should proactively address the logistical issues of the home environment while effectively maintaining or recreating the social elements of rehabilitation. Technical feasibility is necessary but not sufficient; ultimate success depends on clinical feasibility, namely the validation of training compliance and effectiveness in real-world settings.

1.3 Objectives of the study

1.3.1 Background summary and research gaps

Stroke is a growing global health crisis that causes profound and lasting motor disability, imposing a substantial socioeconomic burden. Conventional rehabilitation is fundamentally mismatched with the biological requirements for neuroplasticity, as it fails to provide high-dose, long-term therapy required by discharged survivors with motor impairments. While telerehabilitation has emerged as a promising alternative to overcome these barriers, existing technologies present a critical and unresolved trade-off between logistical accessibility and therapeutic efficacy. Moreover, remote

management has received little attention, despite its crucial role in ensuring long-term implementation and optimizing therapeutic efficacy. Among potential techniques for telerehabilitation, RAT offers a potential means to provide repetitive, intensive, and physically supported therapy within telerehabilitation frameworks. However, the real-world effectiveness of RAT when deployed outside of a highly controlled research environment, such as clinical practice and home-based settings, remains challenging, with three main research gaps:

(1) Lack of frameworks and protocols to support remote management and social interaction in robot-assisted telerehabilitation. Although lay users are expected to interact effectively with robotic systems for motor restoration, with minimal supervision and sustained engagement over long-term rehabilitation, management strategies have been largely overlooked in existing telerehabilitation studies [40, 41]. This necessitates the development of validated frameworks and platforms that ensure continuity of support from both peers and healthcare professionals.

(2) Limited investigation into the translation of laboratory-proven robot-assisted telerehabilitation into real-world clinical services. The transition from controlled experimental settings to clinical implementation introduced unexpected logistical obstacles that could compromise rehabilitative outcomes. Various factors, including patient readiness for independent training, therapist competence in remote guidance, and concerns regarding system safety and usability, may significantly influence this

process [42].

(3) Insufficient evidence on the long-term functional benefits of robot-assisted telerehabilitation. While telerehabilitation has demonstrated short-term improvements, evidence regarding long-term efficacy remains limited and inconclusive. Most existing studies are pilot or feasibility trials characterized by small samples, brief interventions, and follow-up periods seldom exceeding three months. As a result, it is unclear whether the functional gains achieved during telerehabilitation are sustained over time or translate into meaningful improvements in ADL.

1.3.2 Research objectives

This study proposes addressing these research gaps through three primary objectives: (1) framework development and clinical validation, (2) translation to clinical service, and (3) long-term evaluation of robot-assisted telerehabilitation after stroke. Two soft robots were employed, i.e., wrist-hand exoneuromusculoskeleton (WH-ENMS) [32] and ankle-foot exoneuromusculoskeleton (AF-ENMS) [43]. The WH-ENMS, which has been commercialized, was applied in Objectives 2 and 3 for clinical service implementation, whereas the AF-ENMS was utilized in Objective 1 for framework development and clinical validation.

Objective 1: Framework development & clinical validation

Aim 1.1: To develop a telerehabilitation system incorporating a unilateral AF-ENMS

and IoT technology to support data acquisition, remote supervision, and user interaction.

Aim 1.2: To clinically validate the feasibility and effectiveness of the telerehabilitation system for RAGT with patients with chronic stroke.

Objective 2: Translation to clinical service

Aim 2.1: To evaluate the feasibility of translating a WH-ENMS-assisted telerehabilitation program from a controlled laboratory setting to a routine clinical service within a public rehabilitation center.

Aim 2.2: To compare the rehabilitative outcomes in the clinical service setting with those obtained in the laboratory setting.

Objective 3: Long-term efficacy

Aim 3: To evaluate the long-term effects of the WH-ENMS-assisted telerehabilitation program through follow-up evaluations conducted at 3- and 6-month post-intervention.

CHAPTER 2

INTERNET OF EXONEUROMUSCULOSKELETON-ASSISTED LOWER LIMB TELEREHABILITATION AFTER STROKE

2.1 Introduction

Poststroke survivors frequently experience gait and balance impairments, significantly raising the risk of falls [44], diminishing quality of life, and hindering reintegration into the community [45]. Although regaining independent walking is a primary rehabilitation goal, current standard care leaves about 50% of stroke survivors with persistent gait deficits six months after the event, i.e., chronic stroke [14]. The need for continued interventions to enhance lower limb motor recovery is critical, especially given the trend toward earlier hospital discharge [46]. While outpatient treatments are beneficial, their effectiveness is often constrained by limited training sessions that are dwarfed by the patient's extensive inactive time at home, and significant barriers to access due to remote living and shortages of healthcare professionals [47, 48]. These challenges necessitate the development of innovative, remotely supervised rehabilitation approaches that require minimal direct professional involvement.

Common remote approaches for lower limb recovery, such as live video sessions, educational videos, and VR [49], primarily focus on task-specific training and strength exercises. However, these methods provide limited physical assistance to correct

abnormal movements or muscular discoordination, and they often lack a dedicated component for gait training, which is essential for restoring ambulation. In contrast, RAGT has become a promising alternative for delivering repetitive, high-intensity, over-ground therapy by providing mechanical support and dynamic correction of gait cycle [50], thereby not only optimizing rehabilitative outcomes but simultaneously reducing dependence on continuous therapist oversight through automated task execution. RAGT has shown promise in improving motor performance, such as step length and walking capacity, in stroke patients [51]. Despite these benefits, its application remains predominantly confined to clinical settings, with limited exploration of its integration into home-based rehabilitation. One challenge hindering this transition is that the wearability and user-friendliness of the existing robotic systems for self-help usage have not been adequately addressed. Additionally, unsupervised RAGT training at home presents several concerns, including improper adaptation to robotic assistance and safety risks associated with falls during gait training. More investigation is needed to establish safe and effective implementation of over-ground RAGT within home-based telerehabilitation frameworks.

The development of a comprehensive framework for robot-assisted lower limb telerehabilitation after stroke remains in its early stages. Transitioning successfully from clinical to home settings involves more than a mere change in location; it necessitates a robust cyber-physical system capable of remote performance monitoring

and feedback from healthcare professionals to ensure patient safety, treatment adherence, and therapeutic efficacy. Advances in the IoT provide a solid technological foundation for such frameworks. IoT-based architectures support continuous acquisition of training data from on-body or robotic sensors, with secure transmission to cloud repositories for longitudinal performance tracking and analysis [34]. This infrastructure enables healthcare professionals to remotely adjust therapeutic parameters and provide clinical feedback, thereby optimizing clinical workflows and facilitating data-driven tele-management. The feasibility of an IoT-based telerehabilitation platform for post-stroke walking training has been demonstrated [36]. While a home-based program delivered through the platform has been shown to improve gait speed, it failed to enhance other motor outcomes or increase overall training time. Notably, nearly a third of participants even decreased their overall daily walking time [36]. This discrepancy highlights that technical feasibility, while important, is insufficient on its own, underscoring another critical challenge: maintaining sustained patient compliance and engagement in home-based training programs. To translate technical feasibility into clinical efficacy, the telerehabilitation framework will benefit from expanding beyond a cyber-physical approach to incorporate social dimensions, forming a holistic cyber-physical-social system [52]. The social layer is a key component to promote treatment adherence and training engagement [53], especially in the absence of close supervision by therapists and onsite interaction among peers. Evidence suggests that social networks have a significant

influence on health behaviors, as training engagement improves most when patients exercise with others, particularly human partners, rather than alone or with virtual partners [54-56]. Heightened engagement, in turn, can contribute to functional recovery in stroke patients [57, 58]. Potential interventions that integrate social incentives into scalable technology, such as robots and IoT platforms, offer a low-cost approach to boost training engagement and promote positive behavioral changes after stroke [59].

2.2 Study aims

In this study, we introduced the Internet of exoneuromusculoskeleton (Io-ENMS), a novel framework for robot-assisted telerehabilitation. This system integrates IoT technology with AF-ENMS [43] previously developed by our team for RAGT to correct post-stroke gait impairments. While previous clinical trials have demonstrated the AF-ENMS's rehabilitative effectiveness for individuals with chronic stroke under close professional supervision [60], its applicability in unsupervised home settings remained unaddressed. Accordingly, the study was primarily designed to validate this Io-ENMS as a cyber-physical-social system that connects patients and therapists to facilitate home-based RAGT. The system's feasibility and rehabilitative efficacy were evaluated through a single-arm clinical trial involving patients with chronic stroke in their home environments.

2.3 Methods

2.3.1 Io-ENMS-assisted telerehabilitation system

The developed telerehabilitation system leverages current mobile communication networks (4G or above) and soft robotic terminals to deliver RAGT to persons with chronic stroke in unconventional environments, e.g., at home, enabling remote supervision by physical therapists (PTs), cyber interaction among stroke users paired during their rehabilitation, and management of training progress based on the digital cyber networks (Figure 2.1). Specifically, the system integrates the Io-ENMS, which consists of a terminal AF-ENMS (Figure 2.1B) with a wirelessly interfacing mobile App on the side of a stroke user, an encrypted database (MongoDB, Inc.) in a cloud server (Tencent Ltd.) for the secure aggregation and storage of training data automatically transmitted from the App, and a telemonitoring web portal accessible from a networked personal computer for the professionals to access the database for monitoring and managing patients' progress in the telerehabilitation, i.e., administrative platform (Figure 2.1C). Meanwhile, popular communication software, e.g., WhatsApp (Meta Platforms, Inc.) and WeChat (Tencent Holdings Ltd.), are adopted for the internet of messages, connecting multiple patients and a PT to enhance real-time telecommunication and continuous supervision during telerehabilitation.

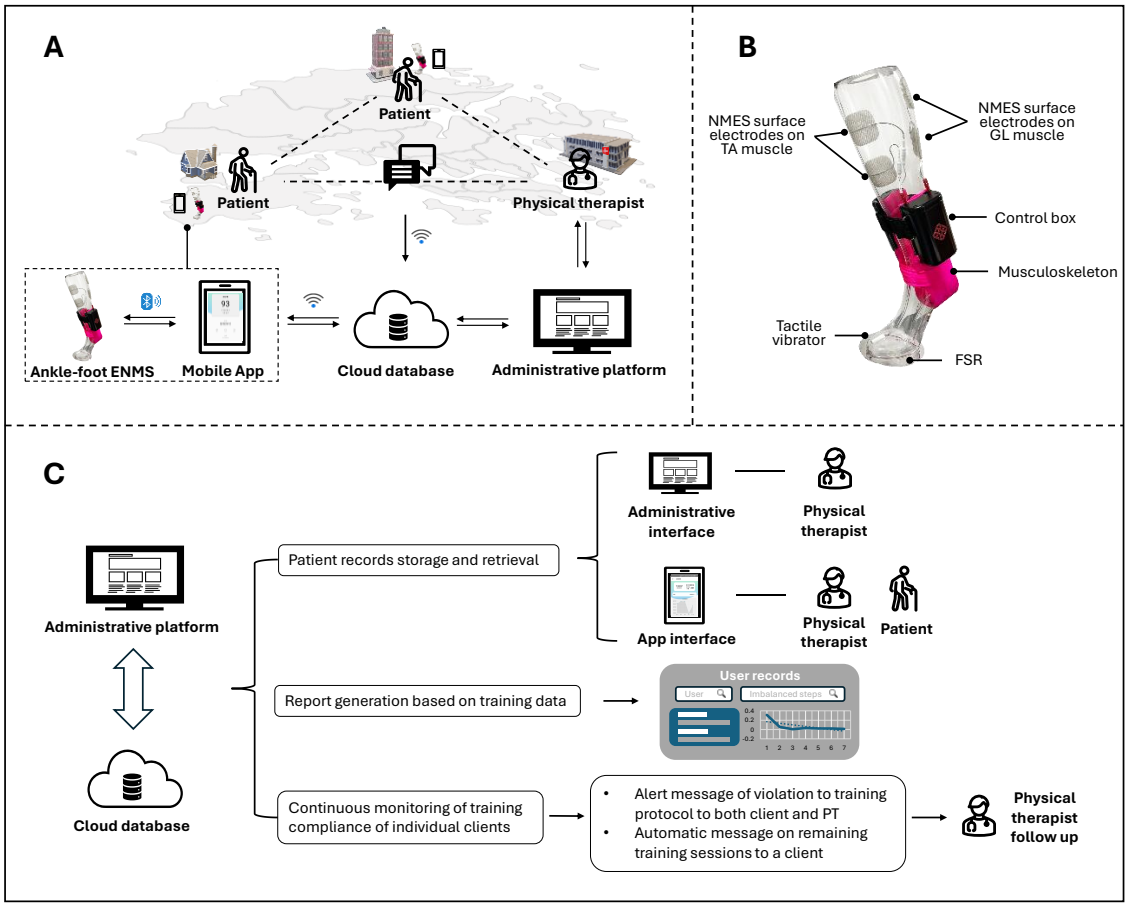

Figure 2.1 (A) Schematic overview of the Io-ENMS-assisted telerehabilitation system for poststroke gait training, **(B)** the terminal AF-ENMS mounted on a plastic ankle-foot model [43], and **(C)** schematic diagram of the administrative platform for telemonitoring and management.

The robotic terminal, i.e., AF-ENMS, for each individual, is a hybrid soft robot for effective neurorehabilitation of foot drop and inversion after stroke, designed by our team [43]. The AF-ENMS is a gait-event driven robot integrating mechanical assistance by a musculoskeleton structure fusing soft pneumatic muscles and rigid exoskeletal extensions into one unit, neuromuscular electrical stimulation (NMES) to target muscles, and vibrotactile feedback within a miniature mechatronic complex. With a

lightweight design of only 0.47 kg, this device can be comfortably worn on the affected lower limb of a patient after stroke using textile braces, making it feasible for unilateral application in hemiplegic gait [60]. The soft-and-rigid musculoskeleton provides mechanical torque fixation above 0.5 Nm to the paretic ankle during a gait cycle's stance phase, thus preventing foot inversion when the pneumatic muscle is inflated. Two-channel NMES (square pulse bursts with 72 V in the amplitude, 40 Hz in the frequency, and 0–300 μs in the pulse width for adjustable stimulation intensities) is applied to the agonist muscles of ankle dorsalflexion (tibialis anterior, TA) during the swing phase, or plantarflextion (lateral gastrocnemius, GL) during the stance phase to correct foot drop, using two pairs of surface electrodes (5×5 cm, PALS Neurostimulation Electrodes, Axelgaard Manufacturing Co., Ltd.). Meanwhile, a tactile vibrator (motor-E610, NFP-Motor Co., Ltd.) positioned between the first and second proximal phalanges provides sensory cues to facilitate self-correction of foot inversion during the stance phase whenever plantar pressure imbalance is detected. The multimodal assistance from the AF-ENMS is coordinated by a microprocessor (STM32F0, STMicroelectronics Inc.) in the control box of the AF-ENMS based on the events within a gait cycle and plantar imbalance, which are recognized by three force sensitive resistors (FSRs; RP-C18.3-LT, LEGACT Co., Ltd.) attached to the bottom of the foot [43]. In the present study, this AF-ENMS was configured as an IoT device for self-help telerehabilitation in home environments.

The mobile App can be installed on compatible mobile devices, e.g., a smartphone (Android 10, connected to a 4G or above network) and communicates with the AF-ENMS control box via Bluetooth module (HC-05, HC Information Tech. Co., Ltd.). Each user needs to register and set up a personal account with password protection before using the Io-ENMS. Meanwhile, the account information of an individual user is used to create an entry in the cloud database to hold the training data, which is subsequently accessible to both the registered user and a professional who takes care of the training. The App provides a user interface (Figure 2.2A) for easy calibration of ENMS parameters, i.e., the assistive level from the NMES and musculoskeleton, as well as the sensitivity of the FSRs for an individual user. In this work, the professional assisted a stroke user with this initial configuration before the training. Specifically, the NMES intensity for the TA was the threshold value to evoke the maximal dorsal flexion of the paretic ankle, and the NMES level for the GL was the maximal sensory threshold without muscle contraction, as TA usually suffers from weakness and GL has spasticity poststroke [61]. The inner air pressure of the musculoskeleton unit for a user was configured with a maximal value of 50kPa when wearing a designated shoe in the training, as the AF-ENMS (Figure 2.1B) can be mounted to a paretic lower limb of the user when wearing their own shoe. It was required that a stroke user should use the same pair of shoes throughout the training, unless inevitable changes, e.g., the shoes are broken. The torque to the ankle joint from the musculoskeleton with 50kPa inside is sufficient for joint fixation in the stance phase [62]. The FSRs' threshold for gait

event recognition was also adjusted individually before training started, i.e., the configuration of the FSR's sensitivity. The above AF-ENMS parameters might need to be calibrated again in the training due to changes in the gait pattern and/or inevitable changes in shoes.

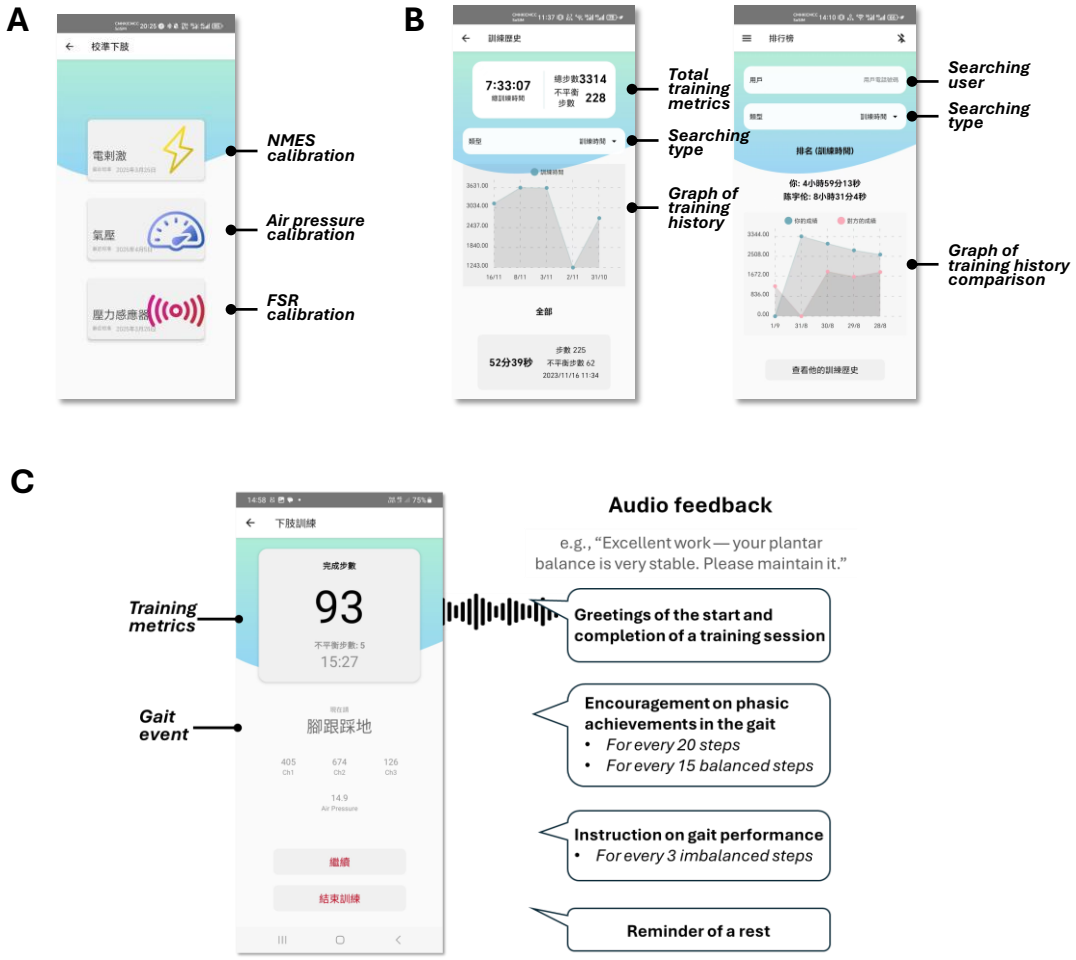

Figure 2.2 App interfaces for telerehabilitation management at the client side. (**A**) The interface for configuring AF-ENMS parameters, including NMES assistance level, FSRs' threshold, and maximal inner air pressure of the ankle module; (**B**) Interfaces of training history for personal review and comparison with a peer; (**C**) Training interfaces for real-time display with audio feedback during training.

Users can initiate or terminate a gait training session directly via a button in the App interface. Additionally, the AF-ENMS control box is equipped with an emergency stop button to enable immediate shutdown in urgent situations. During gait training, the App provides a dynamic interface (Figure 2.2C) that displays real-time training metrics, including training duration, step counts, and imbalanced steps detected during the gait practice of a stroke user, which can be viewed by a caregiver who accompanies the subject [60]. It can also show the training record after the completion of a gait session, including the number of total steps, imbalanced steps, and start-end times of the session (Figure 2.2B); meanwhile, send the record to the cloud server via the current data networks when quitting the App. In the gait practice, the App has the function of providing audio feedback to a stroke user with sounds generated by the mobile device, which includes 1) greetings of the start and completion of a training session, 2) encouragement on phasic achievements in the gait, e.g., verbal praise for every 20 steps and verbal compliments for every 15 balanced steps, 3) instruction on gait performance, e.g., correction reminders for every three imbalanced steps detected, and 4) reminder of a rest after a self-defined period of continuous walking (Figure 2.2C). Finally, the App provides training records of the user retrospectively, which can be compared with the training records of other users (Figure 2.2B).

Cloud-hosted training records are visualized through an administrative platform, enabling remote monitoring of patients' progress by a PT. The functional diagram of

the administrative platform is shown in Figure 2.1C. This platform underpins the storage and retrieval of patient records, providing PTs with access to a terminal display of the administrative platform for record oversight, while the App interface allows both PTs and patients to view these records. Concurrently, the platform generates individualized reports from patient training data, enabling PTs to track the overall training progression. For example, the portal displays all accumulated training data for each user and supports comparative analysis between selected individuals, with key training metrics encompassing cumulative training duration, number of total completed steps, number of imbalanced steps, and the longitudinal trajectory of these metrics over an adjustable timeframe. Building upon these data presentation and analytical capabilities, the platform enables continuous monitoring of the training compliance of individual clients. In instances of training protocol violation, the platform generates and transmits alert messages to both the client and PT. Automatic notifications regarding the remaining training sessions are dispatched to the client. This continuous monitoring function of training compliance by the platform provides data-driven reminders for PT's follow-up, including initiating real-time messaging and conducting home visits, in addition to the traditional hotline communication between the PT and a stroke client, when training at home.

2.3.2 Io-ENMS-assisted self-help telerehabilitation program.

A single-arm intervention study was performed among a cohort of community-dwelling

individuals with chronic stroke. Each participant attended a 20-session gait training program based on the telerehabilitation system. Figure 2.3 shows the workflow of the Io-ENMS-assisted self-help telerehabilitation program. It includes 1) the preparation for home-based training with tutorials and guided training sessions with in-person supervision from a professional, 2) remote coordination and supervision of a pair of stroke users in the single-arm trial, 3) hybrid assistance to a user in need, and 4) evaluations on rehabilitative effects. The requirement of caregiver involvement was determined by the Functional Ambulatory Category (FAC): participants with FAC ≥ 4 were allowed to train independently, while those with FAC = 3 required onsite caregiver supervision during home sessions. Caregivers were encouraged to participate in both the tutorial and guided sessions, assisting with AF-ENMS setup and offering supplementary support during training as needed.

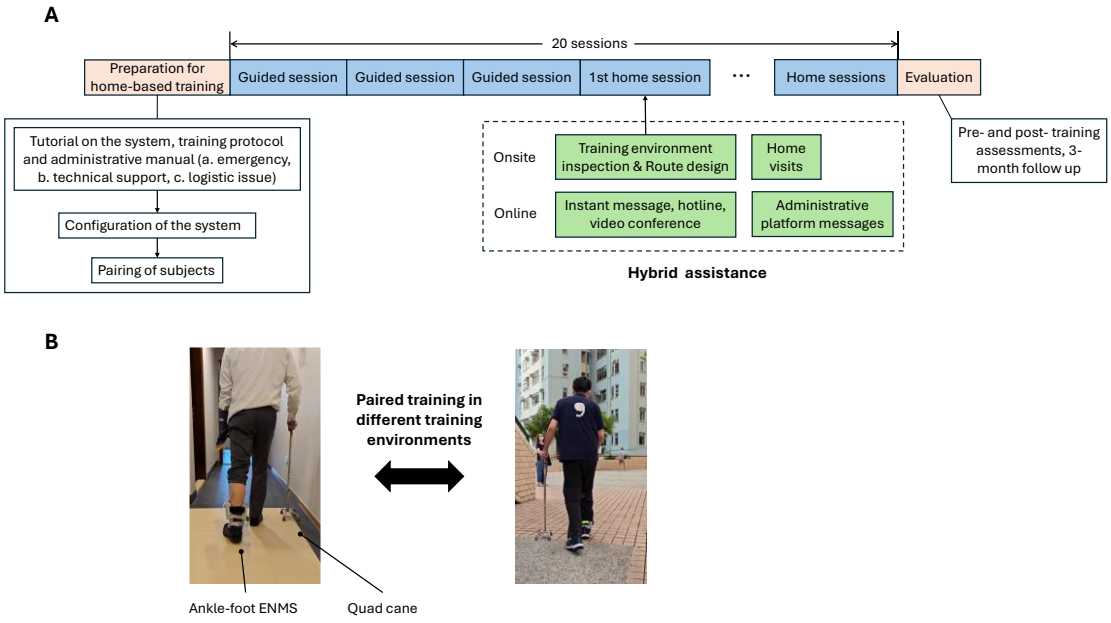

Figure 2.3 Io-ENMS-assisted self-help telerehabilitation program. (**A**) Workflow of the

telerehabilitation program. (**B**) Two paired subjects performing Io-ENMS-assisted gait training in home environments.

2.3.2.1 Subject recruitment

The study protocol was approved by the Human Subjects Ethics Sub-committee of The Hong Kong Polytechnic University. Participants were eligible if they met the inclusion criteria as follows: (1) > six months after onset of stroke, (2) no active inflammatory or pathologic conditions affecting the lower limb joints, (3) no significant visual and auditory impairments, 4) no cognitive impairments as indicated by the Mini-Mental State Examination (MMSE) score > 23 [63], (4) no significant spasticity on ankle joints with the Modified Ashworth Scale (MAS) ≤ 3 [64], (5) mild-to-moderate motor deficit in the affected lower limb, with the ability to stand and walk without manual assistance for an extended period, measured by FAC ≥ 3 [65] and Berg Balance Scale (BBS) ≥ 40 [66].

2.3.2.2 Preparation and guided sessions for participants and their caregivers

At the start of the program, each participant attended preparation for home-based training provided by a PT in a neurorehabilitation laboratory, which included a training tutorial, configuration of the system, and pairing of subjects. The training tutorial covered education on system operation, familiarity with training protocol, and logistic arrangements. Each participant received a set of AF-ENMS and was instructed to install a mobile App. A personal account was created for each participant, and all the necessary

App functionalities would be taught by the PT. A compatible Android smartphone would be provided to participants who do not own one for the duration of the study. The PT provided participants with detailed instructions on the proper donning and doffing procedures for the AF-ENMS and the correct attachment of surface electrodes (Figure 2.1B). To ensure accurate and consistent electrode placement on the paretic leg, the PT marked the designated positions with semi-permanent tattoo stickers and instructed the participant to maintain these markings, or retrace them if they faded, until the last session. Then, the PT conducted individualized calibration of the AF-ENMS parameters (as previously detailed, Figure 2.2A). A user manual on the logistic arrangement was provided, detailing emergency contacts, procedures for technical support, logistic issues, and essential safety education. Separately, to prepare for the logistical aspects of telerehabilitation and promote participant engagement, participants were matched based on mutual selection, age similarity, and baseline impairment levels. A face-to-face meeting was arranged to facilitate familiarity between each pair. Upon commencing the training, each pair and their designated PT were assigned to a dedicated online chat group, which served as the primary online communication platform for the subsequent home sessions.

After the preparation, participants received three guided sessions, supervised by the PT in the neurorehabilitation laboratory, to reinforce their competency in performing home-based self-help training. Each session consisted of 45 minutes of ENMS-assisted

walking, with 5-minute breaks every 15 minutes to prevent fatigue. The level of PT assistance decreased progressively across sessions: the first guided session involved full assistance with device handling and gait training supervision; the second session assisted only as needed, allowing participants to engage more independently; in the third session, participants performed gait training independently under PT's onsite observation. For the guided gait training, the participant was guided to walk along a straight, 10-meter-long corridor free of obstacles using a quad cane in a three-point gait pattern, with two designated turning points. The PT walked alongside the participants without physical contact to prevent falls in their initial usage of the device and provided verbal reminders to help them focus on utilizing assistance from the AF-ENMS. The participants were also guided to follow audio instructions delivered by the smartphone App (Figure 2.2C) for familiarization with the interactions with the AF-ENMS and its feedback. Moreover, the participants were instructed in basic device troubleshooting to facilitate communication in the event of device malfunction, including battery depletion, electrode wire damage, and airbag leakage.

After the three guided sessions, the PT evaluated the participant's competency to perform independent gait training in home settings based on the following capabilities (Table 2.1): 1) the abilities to independently don and doff the AF-ENMS or with caregive assistance, 2) correct operation of App, 3) correct operation of the AF-ENMS, 4) maintenance of desired gait pattern when walking with the system, 5) adherence to

the training protocol, and 6) adherence to administrative management. Additional guided sessions might be provided until a participant was able to pass the assessment.

Table 2.1 Assessment of the competency of participant training in home environments

Competency in using the device	**Yes**	**No**
Don and doff the ENMS		
Operate the App correctly		
Operate the ENMS correctly		
Attach surface electrodes to targeted muscles		
Execute an emergency stop		
Conduct basic troubleshooting		
Competency in compliance with the training protocol	**Yes**	**No**
Perform three-point gait with a quad cane		
Maintain a cadence of around 2 seconds		
Follow the App's audio indication		
Understand the requirement of the training intensity, 45-90 min/day, 3-6 days/week, for 20 sessions in total		
Understand safety precautions and warnings associated with home-based training		
Competency to follow administrative arrangements	**Yes**	**No**
Communicate via online group with peer/PT in real-time		
Familiarize with the emergency contacts		
Access and reference the user manual as needed		
When participants were accompanied by caregivers, caregivers could assist with the training setup. If any checklist item received a "No" response, participants were deemed unable to conduct home-based training independently, while those with "Yes" responses to all items were classified as capable.		
Experiment operator: _____ Patient Signature: _____		
Date: Number of current sessions:		

2.3.2.3 Hybrid management during telerehabilitation

All recruited participants began their home-based training after the guided sessions, provided they passed the assessment. The participants were advised to engage in the ENMS-assisted gait training program lasting 45-90 minutes per session, conducted three to six sessions a week over a continuous 7-week period. This flexible range was

intended to enhance participant engagement while avoiding muscular fatigue. The training could be completed either as a single continuous period or distributed across multiple shorter periods throughout the day [48]. At the first home session, the PT delivered the AF-ENMS device and its accessories to the participant's residence. The PT assessed the home environment and its vicinity to identify several appropriate gait training routes, together with the participant. The training route, which could be either indoors (e.g., corridors) or outdoors (e.g., a quiet path in a park), was required to involve a straight, level, non-slip, obstacle-free path allowing continuous walking, with a minimum length of 10 meters and a minimum width of 1.5 meters for potential caregiver-assisted ambulation. The preferred configurations included either a looped route with no more than three turns to support repetitive training or a straight path terminating in a turn for cyclical traversal. Training sessions were preferentially scheduled during off-peak hours or in reserved corridors to minimize environmental interference. Additional environmental requirements included adequate lighting, proper ventilation, and a stable internet connection (via Wi-Fi or mobile data) for remote communication. Following the supervision in the guided sessions, the PT supervised the participant during a 45-minute home-based RAGT session to ensure compliance and consistency with laboratory-based sessions. Before each training session, participants were required to inspect their training environment for potential hazards, e.g., slippery surfaces after rain, on which occasions participants were supposed to choose another route. Caregivers (if any) were to remain within 0.5 meters to provide

immediate assistance in case of discomfort or falls. In the event of an accident or system malfunction during unsupervised training, participants were required to contact the PT immediately.

During telerehabilitation, this program adopted a hybrid management approach combining continuous online supervision with targeted onsite visits to provide adequate professional and technical support promptly (Figure 2.3A). In addition to remote monitoring via the online administrative platform, the PT maintained regular contact with the paired participants primarily through instant messaging, as well as hotline support and video conferencing. The PT delivered tailored clinical guidance to each pair through ongoing communication, including reminders for training compliance, feedback on movement quality, technical troubleshooting, and emotional encouragement. Moreover, a weekly checklist was reviewed for each participant via video calls to identify and address any potential concerns (Table 2.2). Following the weekly review, the PT provided each pair with progress updates and brief clinical feedback reports via their chat group. Home visits were arranged when online management was deemed insufficient, e.g., system malfunctions or significant training protocol deviation that could not be resolved online, the PT would provide professional advice and ensure system replacements within one working day to prevent protocol deviations. In-person visits were also initiated for requests from a participant and any unexpected accidents reported during the training.

Table 2.2 Weekly checklist for monitoring compliance and ensuring safety.

When using the device:	**Yes**	**No**
Any difficulties using the device?		
Are tattoo stickers available for electrode attachment?		
Are there any device malfunctions?		
When during the training	**Yes**	**No**
Are there any issues with gait training?		
Are there any adverse events related to the training?		
Are there any challenges maintaining prescribed intensity?		
Are there any questions regarding logistic arrangements?		
When participants were accompanied by caregivers, caregivers were permitted to participate in the weekly checklist review. If any checklist item received a **"Yes"** response, the presence of an issue requiring intervention, the PT will provide necessary assistance to resolve identified challenges.		
Experiment operator: _____		
Date: Number of current sessions:		

2.3.3 Evaluation of feasibility and effectiveness of the telerehabilitation

The feasibility of the Io-ENMS-assisted telerehabilitation was assessed based on several aspects: (1) compliance with the training protocol and progress; (2) smoothness of remote management; and (3) participant experience and satisfaction. The rehabilitative effects achieved by the participants were evaluated by clinical assessments, gait analyses, and EMG evaluations at three time points, i.e., one week pre-training, one week post-training, and at 3-month follow-up (3MFU).

2.3.3.1 AI-assisted administrative analysis of daily chat logs

In this study, most remote management was delivered through online group chats between a PT and paired stroke patients. These chat logs served as a rich source of information, reflecting patient needs, challenges, training experiences, and interactions

during telerehabilitation. To understand the content of these communications, two PTs manually reviewed a subset of the dataset and categorized messages into seven topics: training schedule and progress, technical inquiry and support, training inquiry and guidance, training experience, emotional support, conversational conventions, and others [67, 68]. Given the scalability needs and the growing capabilities of large language models (LLMs), we employed ChatGPT (GPT-4o) for automatic message classification. GPT-4, the latest generation of OpenAI's LLMs, offers high accuracy and speed in zero-shot identification of topics and emotions [69, 70]. A chatbot based on GPT-4o (8k) was developed and deployed as an API service, which was accessed using a code editor (Visual Studio Code, Microsoft Corp.) to automatically assign topic labels to each message using a zero-shot learning approach. A prompt template, based on key elements such as context, instruction, output indicator, and input data [69], was designed to guide the querying process in the chatbot, as illustrated in Figure 2.4.

Context	Here is a chat log from a home-based robot-assisted gait training program after stroke. Chat participants include a physical therapist who coordinate the chat, two stroke patients, and their caregivers. You have to classify each message within the chat log into one of the following categories: **-Training schedule and progress**: Participant's daily training schedule and training progress such as frequency and duration. **-Technical inquiry and support**: Technical issues related to the robot usage, including charging, data transmission, hardware failure, as well as repair and replacement. **-Training inquiry and guidance**: Other training-related questions except for training schedule and technical issues, as well as recommendations and feedback based on training data and observations. **-Training experience:** Participant reported experiences during the training program, such as subjective perception of system usage, training improvements, and any discomfort encountered. **-Emotional support:** Supportive and encouraging communication between the group members. **-Conversational conventions:** Message containing greeting words, for example 'Hello', 'good morning', and closer words, for example 'Thanks', 'ok'. **-Others:** Any other kind of message that doesn't fit into the previous categories, such as personal stories or general conversations.
Instruction	Each message should be classified into one of the categories. Do not include other categories except those defined above. Categorization should not be overlapped.
Output indicator	Return a complete JSON string that is compatible with a Python dictionary. The format should be: {'message': 'category'}.
Input data	Group chat log: <chat log>

Figure 2.4 Prompt used to query the chatbot for topic-based message classification

Prior to analysis, all chat logs were documented and quantified by the total volume of information exchanged in the online groups, including texts, images, videos, stickers, documents, and links. These logs, originating from several cyber-paired groups, covered a period from the group's creation to the completion of all training sessions for the paired participants. A single analytical dataset was developed by concatenating chat messages from all chat attendees, with minimal pre-processing including (1) removing empty and unrecognizable messages, (2) audio-to-text transformation, and (3) removing private messages, such as phone numbers, from text manually. The dataset consisted of three columns: message timestamp, user handle, and a textual chat message. Non-text elements (e.g., images, videos, stickers, documents, and links) were retained as file names within the text field to support traceability and contextual interpretation. Each chat message was treated as one "document", i.e., the natural grouping to understand the free text, for analysis.

2.3.3.2 Developed questionnaire on patient experience and satisfaction

A customized questionnaire was developed to evaluate user experience within the telerehabilitation program, drawing upon the Usefulness, Satisfaction, and Ease of Use (USE) Questionnaire [71] and the Intrinsic Motivation Inventory (IMI) [72]. Both instruments utilized a 7-point Likert scale. USE was employed to evaluate the usability of the program, which includes four dimensions: Usefulness, Ease of Use, Ease of Learning, and Satisfaction. USE, previously applied to RAT research [67, 73], was

scored according to the established guideline [74]. Scores for each of its four dimensions were calculated by summing the relevant item scores, then dividing by the total possible score for that dimension to generate a normalized value. A tailored 12-item version of the multidimensional IMI [75, 76] was used to assess intrinsic motivation. Items were organized into six subscales: interest/enjoyment, perceived competence, effort/importance, pressure/tension, value/usefulness, and relatedness. Subscale scores were computed by averaging the item scores within each subscale; these averages were then normalized by dividing by the maximum possible response of seven [72]. Finally, several additional custom questions were developed to further investigate the participants' overall training experience within the telerehabilitation program.

2.3.3.3 Evaluation of rehabilitation effectiveness on motor restoration

A blinded assessor who did not know the study content conducted an independent evaluation of the rehabilitation effectiveness at three time points: (1) pre: within a week before the first training session, (2) post: within the next three days after the last training session, (3) 3MFU: 3 months after the last training session. All participants were evaluated without the AF-ENMS. Clinical assessments included the following: (1) the Fugl-Meyer Assessment for Lower Extremity (FMA-LE), to evaluate motor function; (2) MAS at the hip, knee, and ankle joints, to assess joint spasticity during passive muscle stretching; (3) FAC, a six-level scale assessing functional ambulation on level

and uneven surfaces; (4) BBS for balance assessment; (5) the 10 Meter Walk Test (10MWT) to measure gait speed over a short distance. The primary indicators of rehabilitative effectiveness were FMA-LE, reflecting voluntary motor function, and BBS, assessing balance and coordination, respectively, and both are sensitive to RAGT [77, 78]. The remaining measures served as supplementary references to provide a comprehensive evaluation of participants' functional performance.

Gait analysis was performed with two primary systems: (1) an eight-camera, three-dimensional (3D) motion capture system (Vicon Motion Systems, Oxford, UK) to track body kinematics, and (2) an in-shoe pressure measurement system (Novel Pedar-X, Novel Inc.) to record plantar loading. During the motion capture, participants were instructed to walk independently for 6 meters thrice without wearing the AF-ENMS. For analysis, two full gait cycles from the mid-portion of each trial were selected to minimize variability arising from gait initiation and termination. Peak joint angles were calculated for the ankle, knee, and hip in both the sagittal and frontal planes across the stance and swing phases through the Dynamic Plug-in Gait Model. The ankle dorsiflexion angle (swing phase) and foot inversion angle (stance phase) at the paretic limb were the primary kinematic outcomes to measure the training effects on correcting gait disturbances. The spatiotemporal gait parameters, including cadence, walking speed, step length, step width, and stance and swing time, were also calculated. The in-shoe pressure measurement system was adopted to quantify bilateral plantar pressure

distribution, including contact area and peak pressures across six predefined foot regions, i.e., medial forefoot (MF), lateral forefoot (LF), medial midfoot (MM), lateral midfoot (LM), medial rearfoot (MR), and lateral rearfoot (LR) [79]. Participants were instructed to repeat the 6-meter-long overground walking thrice while wearing the Pedar-X System. Two full gait cycles in the mid-portion of each trial were extracted to minimize variability arising from gait initiation and termination.

Muscle activity was measured by wireless electromyography (EMG) electrodes (Delsys Corp., Natick, MA, USA) from the TA, GL, vastus medialis oblique (VMO), and biceps femoris (BF) muscles [80]. Before the walking trials, a 5-second resisted isometric maximal voluntary contraction (MVC) was recorded for each muscle for normalization. Wireless EMG data were acquired simultaneously with 3D motion capture while walking 6-m-long overground. Collected EMG signals were employed for the calculation of the EMG activation level [81]. The activation levels of a muscle at both the stance and swing phases were used to analyze the muscle activation, which is the mean amplitude of the EMG envelope normalized to the maximum value obtained during MVCs.

2.3.4 Statistical analysis

All statistical analysis was conducted using SPSS Statistics version 26 (IBM, Chicago, IL, USA). The Shapiro-Wilk test [82] determined normality for all variables with the exception of MAS and FAC. Clinical outcomes across baseline, post-intervention, and

3MFU assessments were examined using one-way repeated-measures analysis of variance (ANOVA), with post-hoc pairwise comparisons conducted via paired t-tests. Non-parametric alternatives, including the Friedman test with Wilcoxon signed-rank follow-ups, were utilized where distributional assumptions were violated. Gait metrics underwent two-way repeated-measures ANOVA to examine main effects of time (pre-, post-, 3MFU) and limb (affected/unaffected), along with their interaction. Subsequent limb comparisons employed paired t-tests, while temporal differences were assessed with one-way repeated-measures ANOVA. All post-hoc analyses incorporated Bonferroni correction for multiple comparisons. A significance level was set at 0.05 ($p \leq 0.05$), with additional significance thresholds established at $p \leq 0.01$ and $p \leq 0.001$.

2.4 Results

2.4.1 Participants

In total, 36 individuals with chronic stroke from the local community were screened, of whom 19 satisfied the eligibility requirements and were enrolled in the study. All participants provided written informed consent before the study began. One participant dropped out during the pre-training evaluation because of illness, and two participants discontinued their involvement during the training due to illness or work conflict. Figure 2.5 illustrates the Consolidated Standards of Reporting Trials (CONSORT) flowchart of the training program. A final cohort of 16 participants completed the training and were consequently incorporated into the data analysis. The mean ±

standard deviation (SD) time since stroke was 6.94 ± 6.60 years, and their average age was 53.88 ± 14.49 years. The cohort consisted of 4 females, 9 individuals with hemorrhagic stroke, and 7 individuals with left hemiparesis. Among the participants, 12 had attained an education level lower than a bachelor's degree, and 2 were employed.

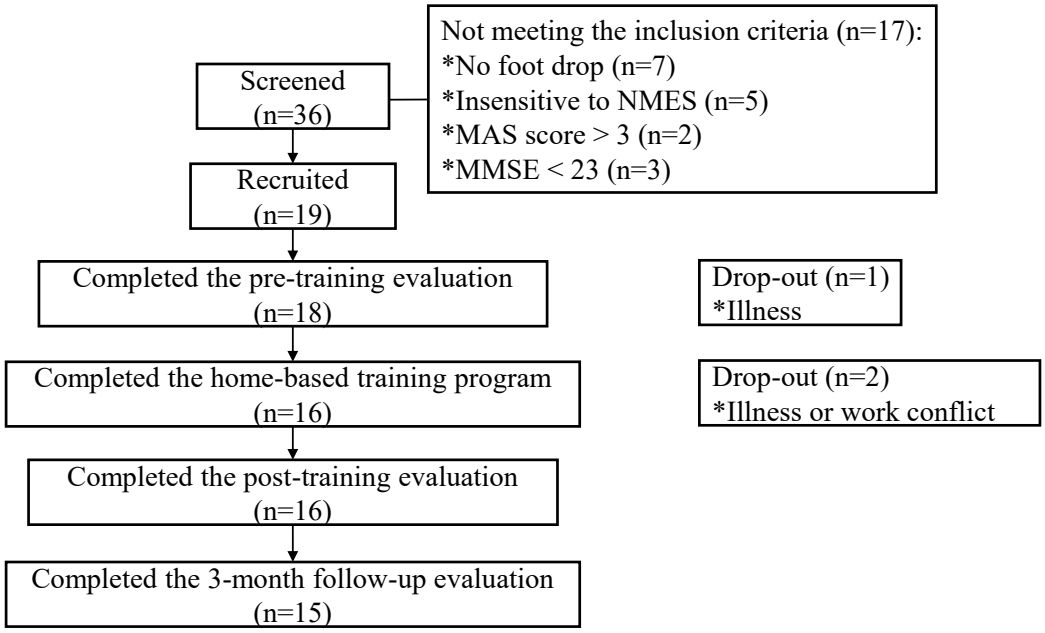

Figure 2.5 The CONSORT flow diagram

2.4.2 Training feasibility

All 16 participants were deemed competent to proceed with home-based training following completion of three guided sessions. The training was completed with caregiver support by 11 participants, while the remaining 5 individuals successfully conducted the program independently. 6 participants encountered AF-ENMS malfunction, and the device was repaired or replaced within a working day. An adverse event (e.g., leg pain in proximity to the NMES application site) was reported by a

participant during the home training because of excessive training over 90 minutes per day; the symptom resolved after the participant performed self-stretching exercises targeting the TA muscle; however, she ultimately decided to withdraw from the program.

According to training data stored in the cloud database, the average training frequency was 4.54 ± 0.99 (mean ± SD) days/week (ranging from 3 to 6 days/week). The average training duration per day after the three guided sessions was 52.10 ± 10.65 (mean ± SD) minutes, which is over the regular training period, i.e., 45 minutes. During the three guided sessions, the average training steps per session were 226.70 ± 67.37 (mean ± SD) steps, and the average imbalanced steps per session were 76.00 ± 75.01 (mean ± SD) steps. For the remaining home sessions, the average training steps per session were 330.00 ± 123.98 (mean ± SD) steps, and the average imbalanced steps per day were 40.08 ± 79.48 (mean ± SD) steps. The training duration increased during the home sessions, and the imbalanced steps/total steps decreased significantly ($p \leq 0.001$) throughout the 20 training sessions (Figure 2.6A). The average training periods per day were 1.51 ± 1.00 (mean ± SD) periods/day (ranging from 1 to 7 sessions/day), and 12 participants conducted distributed training in 83 days. Training sessions were primarily scheduled on weekdays, with 80.15% of training days occurring on weekdays. This distribution of training time choices was attributed to the social activities of the participants or their caregivers on weekends.

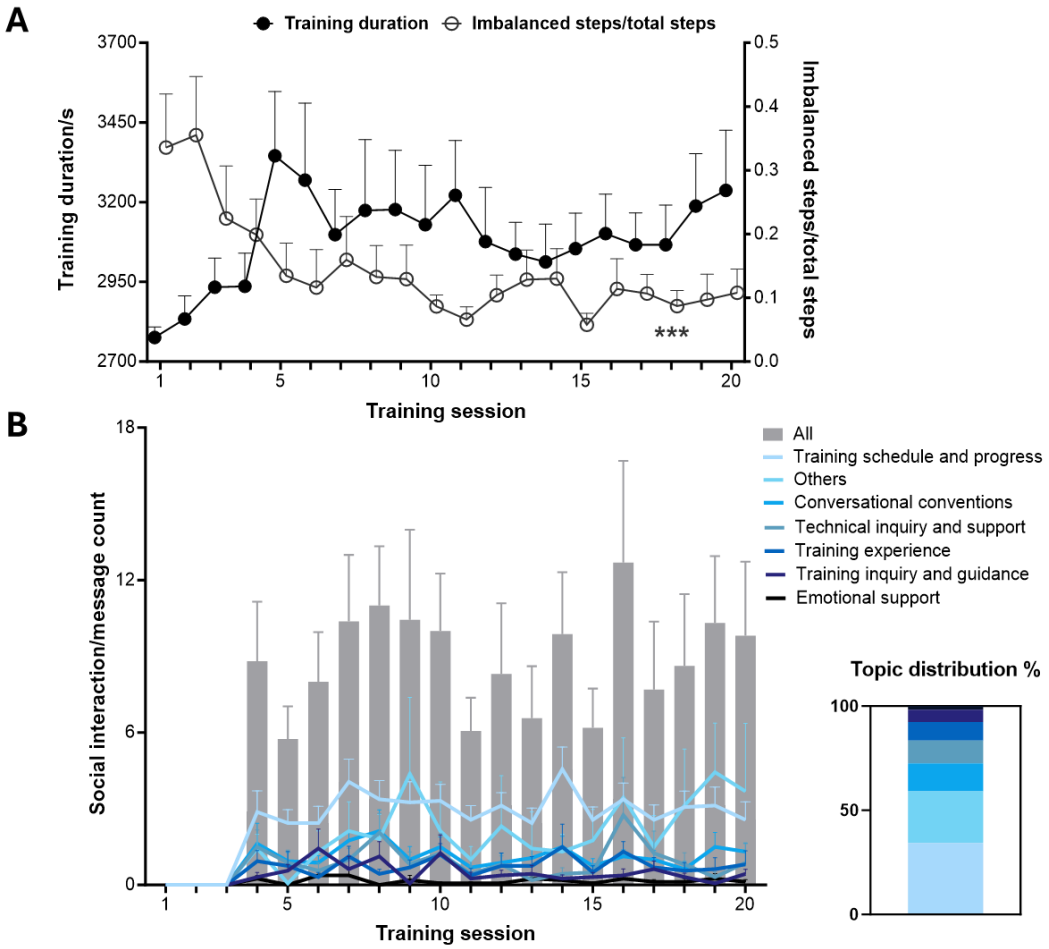

Figure 2.6 (A) training data and **(B)** interactions of participants across the 20 training sessions. Data are shown as means ± standard error (SE). The symbol "*" denotes a significant difference, with three symbols for $p \leq 0.001$.

The characteristics of chat logs for PT and participants during the program are shown in Table 2.3. A total of 4,675 messages were exchanged among all chat groups, with 2,407 from stroke participants and 2,268 from the PT. The topic distribution of chat messages by stroke participants: training schedule and progress (35.15%), others (26.59%), conversational conventions (12.92%), technical inquiry and support (10.88%), training experience (7.56%), training inquiry and guidance (5.28%), and

emotional support (1.62%). For the PT, the topic distribution was as follows: training inquiry and guidance (21.47%), others (20.11%), conversational conventions (17.24%), emotional support (15.08%), technical inquiry and support (13.49%), and training schedule and progress (12.61%). Throughout the home-based sessions, interactions for participants within the online groups remained consistent (Figure 2.6B), averaging 8.85 ± 10.08 (mean ± SD) messages per session. No significant differences were found in the total number of messages or in any specific topic between sessions.

Table 2.3 Chat log characteristics for PT and participants across the program.

Chat log parameters	**PT**	**Participants**
Message count	2268	2407
Message type		
Text	2115	1564
Image	62	644
Video	13	95
Sticker	75	66
Document	1	3
Link	2	35
Message topic		
Training related	62.65%	60.49%
-Training schedule and progress	12.61%	35.15%
-Training inquiry and guidance	21.47%	5.28%
-Technical inquiry and support	13.49%	10.88%
-Training experience	0%	7.56%
-Emotional support	15.08%	1.62%
Conversational conventions	17.24%	12,92%
Others	20.11%	26.59%

After the training, participants reported a significantly higher score in the

interest/enjoyment subscale of IMI during home-based sessions compared with guided sessions. The normalized score of all subgroups of USE is around 80%. Regarding feedback from participants, they believed that they acquired effective supervision, communicated training experience, and acquired peer support through the whole telerehabilitation program. The values for patient subjective experience during the guided or home training period are shown in Table 2.4.

Table 2.4 Training experience by questionnaire results.

USE	Mean% ± SD%		
Usefulness	80.67% ± 15.52%		
Ease of Use	79.41% ± 13.09%		
Ease of Learning	79.41% ± 15.54%		
Satisfaction	81.93% ± 15.59%		
IMI	**Guided sessions**	**Home-based sessions**	**Pair t-test**
	Mean% ± SD%		*P (Cohen's d)*
Interest/Enjoyment	65.97% ± 28.74%	76.05% ± 23.95%	0.018*(0.381)
Perceived Competence	68.07% ± 19.09%	67.23% ± 15.58%	0.826(0.048)
Effort/Importance	80.67% ± 15.72%	82.77% ± 15.58%	0.492(0.134)
Pressure/Tension	70.59% ± 23.13%	76.47% ± 14.23%	0.207(0.306)
Value/Usefulness	82.77% ± 13.85%	84.45% ± 15.20%	0.387(0.116)
Relatedness	81.51% ± 16.57%	81.51% ± 14.74%	1.000(0.000)

The superscript "*" denotes a significant difference, with 1 superscript for $p \leq 0.05$.

2.4.3 Training effectiveness

Figure 2.7 illustrates evaluation results for clinical assessments, gait analysis, and EMG analysis. After the training, FAC, FMA-LE, and BBS were significantly improved after

the training and at 3MFU. The specific values for clinical assessments conducted at baseline, post-intervention, and at 3MFU are presented in Table 2.5. Significant increase in the peak ankle dorsiflexion angle on the affected side during swing phase was observed immediately post-training; however, this improvement was not maintained at the 3MFU. There were notable decreases in the peak angle of ankle inversion on the affected side during the stance phase, and significant increases in the peak angle of knee flexion on the affected side during the swing phase. After the completion of 20 training sessions, spatiotemporal parameters, including the swing time of the unaffected side and step length of the affected side, were significantly increased, and the improvements lasted to 3MFU. Conversely, the walking speed on both sides significantly decreased after the training but demonstrated a significant elevation at 3MFU compared with the post-training period. Significant increase was found in the peak pressure of LR on both sides after the training and at 3MFU. Increases in the peak pressure of MR were observed bilaterally, with a significant rise on the unaffected side immediately after training and on the affected side at 3MFU. Following the training, a significant reduction was observed in the activation of GL on the unaffected side during the stance phase and BF on the affected side during the swing phase. The specific values for gait parameters and EMG activation level before, after, and 3 months after the training intervention are presented in Table 2.6.

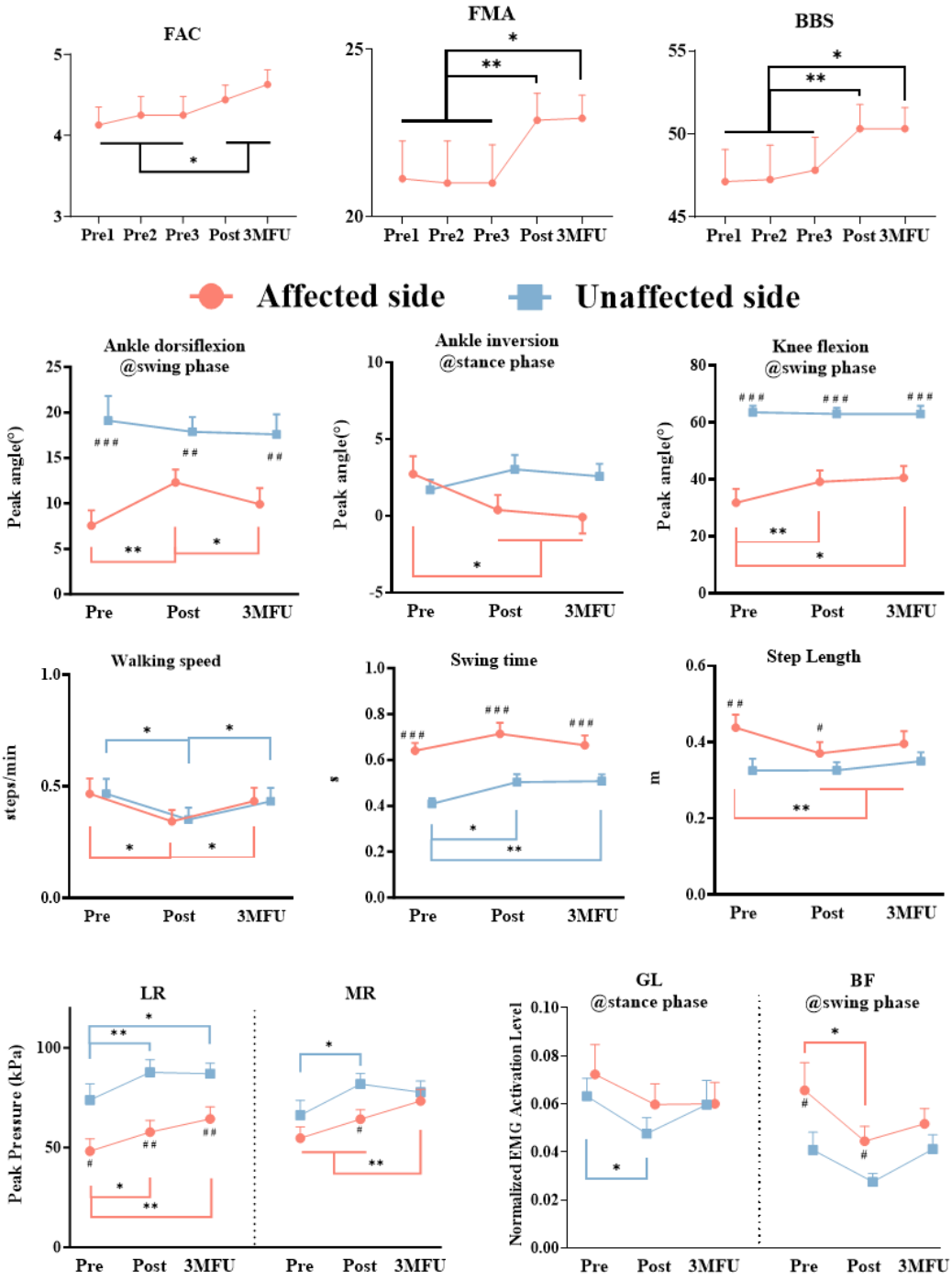

Figure 2.7 Rehabilitation outcome, including clinical scores, kinematic parameters, plantar pressure, and EMG parameters measured at pre-, post-, and 3MFU assessments. Values are presented as mean ± SE. The symbols "*" and "#" indicate the significant difference regarding time points and limbs, respectively, with 1 symbol denoting $p \leq$

0.05, 2 symbols denoting $p \leq 0.01$, and 3 symbols denoting $p \leq 0.001$.

Table 2.5 Clinical variables at the pre-, post-, and 3MFU assessments.

Clinical assessments		Pre1	Pre2	Pre3	Post	3MFU	One-way Repeated Measures ANOVA
		Mean (95% confidence interval)					*P (Partial η^2)*
FMA-LE (max. 34)		21.13 (18.71~23.54)	21.00 (18.32~23.68)	21.00 (18.55~23.45)	22.88 (21.16~24.59)	22.94 (21.46~24.41)	0.005**(0.367)
BBS (max. 56)		47.13 (43.00~51.25)	47.25 (42.85~51.65)	47.81 (43.58~52.05)	50.31 (47.21~53.42)	50.31 (47.58~53.04)	0.004**(0.363)
10MWT (m/s)		0.67 (0.48~0.86)	0.69 (0.51~0.88)	0.69 (0.50~0.89)	0.67 (0.51~0.84)	0.69 (0.51~0.87)	0.722(0.021)
Clinical assessments		**Pre1**	**Pre2**	**Pre3**	**Post**	**3MFU**	**Friedman Test**
		Mean (95% confidence interval)					*P (Kendall's W)*
MAS (max.4)	Hip	0.83 (0.39~1.26)	0.96 (0.50~1.42)	0.85 (0.51~1.19)	0.68 (0.27~1.08)	0.86 (0.37~1.36)	0.178(0.108)
	Knee	0.91 (0.49~1.34)	0.68 (0.23~1.12)	0.71 (0.33~1.10)	0.55 (0.09~1.01)	0.71 (0.20~1.22)	0.092(0.149)
	Ankle	2.05 (1.56~2.54)	1.68 (1.11~2.24)	1.73 (1.21~2.24)	1.50 (1.09~1.91)	1.70 (1.21~2.19)	0.290(0.077)
FAC (max. 5)		4.13 (3.65~4.60)	4.25 (3.75~4.75)	4.25 (3.75~4.75)	4.44 (4.05~4.83)	4.63 (4.24~5.01)	0.004**(0.352)

The superscript "*" denotes a significant difference, with 2 superscripts for $p \leq 0.01$.

Table 2.6 Kinematics, plantar pressure, and EMG variables at the pre-, post-, and 3MFU assessments.

Gait Parameters		Pre	Post	3MFU	Two-way Repeated Measures ANOVA		
		Mean (95% confidence interval)			*Time* *P (Partial η^2)*	*Limb* *P (Partial η^2)*	*Time* Limb* *P (Partial η^2)*
Kinematics - peak angles in the sagittal plane (°)							
Ankle dorsiflexion @stance phase	Affected side	19.63(15.88~23.37)	20.60(16.00~25.20)	20.20(16.83~23.57)	0.926(0.005)	0.005** (0.416)	0.532(0.041)
	Unaffected side	27.16(22.79~31.54)	26.84(23.62~30.06)	26.43(23.13~29.73)			
Ankle dorsiflexion @swing phase	Affected side	7.69(4.10~11.29)	11.73(8.69~14.77)	9.54(5.82~13.26)	0.260(0.086)	0.001*** (0.535)	0.015*(0.243)
	Unaffected side	19.11(13.34~24.88)	17.87(14.41~21.33)	17.60(12.88~22.31)			
Knee extension @stance phase	Affected side	3.90(-0.84~8.63)	3.92(0.16~7.67)	2.87(-1.74~7.47)	0.933(0.005)	0.001*** (0.556)	0.609(0.033)
	Unaffected side	11.84(9.22~14.46)	11.88(8.50~15.26)	12.40(9.05~15.74)			
Knee flexion	Affected side	31.77(21.31~42.23)	39.15(30.63~47.68)	40.58(31.90~49.26)	0.075(0.178)		

@swing phase	Unaffected side	63.55(58.74~68.36)	62.98(58.40~67.56)	62.97(56.94~69.00)		0.000*** (0.760)	0.002** (0.335)
Hip extension @stance phase	Affected side	5.29(-1.13~11.70)	4.40(-0.54~9.35)	2.09(-3.04~7.22)	0.183(0.107)	0.003** (0.451)	0.216(0.097)
	Unaffected side	0.33(-5.70~6.36)	-0.11(-5.93~5.70)	-4.02(-8.17~0.13)			
Hip flexion @swing phase	Affected side	34.21(26.80~41.63)	33.85(27.30~40.40)	32.49(26.24~38.74)	0.726(0.021)	0.042* (0.247)	0.991(0.001)
	Unaffected side	40.25(34.67~45.83)	39.77(34.31~45.22)	38.61(33.65~43.56)			
Kinematics - peak angles in the frontal plane (°)							
Ankle inversion @stance phase	Affected side	2.65(0.17~5.12)	0.49(-1.60~2.57)	0.13(-2.11~2.36)	0.411(0.058)	0.217(0.099)	0.006** (0.289)
	Unaffected side	1.71(0.33~3.09)	3.03(1.04~5.02)	2.58(0.85~4.31)			
Ankle eversion @swing phase	Affected side	-2.25(-4.53~0.04)	-3.38(-5.80~-0.97)	-4.63(-6.56~-2.69)	0.063(0.169)	0.201(0.107)	0.410(0.058)
	Unaffected side	-2.00(-3.48~-0.53)	-1.39(-3.10~0.33)	-3.19(-4.96~-1.42)			
Knee valgus @stance phase	Affected side	-3.24(-6.61~0.12)	-3.25(-6.57~0.07)	-3.47(-6.66~-0.29)	0.588(0.035)	0.002** (0.470)	0.648(0.029)
	Unaffected side	-7.42(-11.53~-3.31)	-5.72(-8.95~-2.50)	-7.82(-10.72~-4.93)			
Knee varus @swing phase	Affected side	14.56(9.65~19.48)	15.52(10.59~20.45)	11.16(5.86~16.47)	0.080(0.155)	0.684(0.011)	0.566(0.037)
	Unaffected side	11.81(4.23~19.38)	16.75(10.00~23.49)	9.71(2.74~16.69)			
Hip adduction @stance phase	Affected side	7.84(4.98~10.71)	7.85(5.62~10.07)	6.34(4.41~8.27)	0.030* (0.209)	0.047* (0.238)	0.307(0.076)
	Unaffected side	3.51(0.78~6.24)	5.20(2.13~8.28)	3.91(1.37~6.45)			
Hip abduction @swing phase	Affected side	-2.44(-5.83~0.95)	-3.96(-7.32~-0.61)	-3.51(-6.55~-0.47)	0.907(0.007)	0.034* (0.267)	0.358(0.066)
	Unaffected side	-8.56(-11.51~-5.61)	-7.59(-10.25~-4.92)	-7.65(-10.21~-5.08)			
Kinematics - spatiotemporal parameters							
Cadence (steps/min)	Affected side	66.67(54.64~78.70)	56.52(43.21~69.84)	63.67(51.31~76.03)	0.098(0.143)	0.226(0.096)	0.261(0.086)
	Unaffected side	67.33(55.1~79.56)	57.47(44.37~70.56)	63.30(51.07~75.53)			
Walking Speed (m/s)	Affected side	0.47(0.32~0.62)	0.34(0.23~0.46)	0.43(0.30~0.57)	0.008** (0.278)	0.542(0.025)	0.285(0.080)
	Unaffected side	0.47(0.32~0.62)	0.35(0.23~0.47)	0.43(0.30~0.57)			
Step Length (m)	Affected side	0.44(0.36~0.51)	0.37(0.31~0.44)	0.40(0.32~0.47)	0.036* (0.211)	0.015* (0.356)	0.002** (0.371)
	Unaffected side	0.33(0.26~0.39)	0.33(0.28~0.37)	0.35(0.30~0.40)			
Step Width (m)	Affected side	0.23(0.21~0.26)	0.24(0.21~0.27)	0.24(0.21~0.27)	0.773(0.017)	0.658(0.013)	0.865(0.01)
	Unaffected side	0.23(0.21~0.26)	0.24(0.21~0.27)	0.24(0.21~0.27)			
Stance Time (s)	Affected side	1.51(1.09~1.93)	1.93(1.27~2.60)	1.58(1.01~2.15)	0.161(0.115)		0.540(0.04)

	Unaffected side	1.68(1.22~2.14)	2.16(1.43~2.89)	1.80(1.14~2.45)		0.001*** (0.559)	
Swing Time (s)	Affected side	0.64(0.57~0.71)	0.71(0.61~0.82)	0.66(0.57~0.75)	0.010** (0.265)	0.000*** (0.731)	0.060(0.171)
	Unaffected side	0.41(0.36~0.46)	0.50(0.43~0.58)	0.51(0.44~0.57)			
Contact Area (cm^2)	Affected side	115.95(101.71~130.19)	121.53(108.00~135.07)	121.09(106.42~135.76)	0.066(0.176)	0.004** (0.459)	0.782(0.017)
	Unaffected side	139.62(130.61~148.63)	142.66(134.91~150.40)	142.74(132.77~152.71)			
Peak Pressure (kPa)							
MF	Affected side	61.37(44.53~78.21)	61.50(46.41~76.60)	66.25(50.84~81.67)	0.442(.057)	0.002** (.506)	0.423(0.060)
	Unaffected side	87.83(70.72~104.93)	82.22(66.33~98.12)	86.92(68.97~104.86)			
LF	Affected side	39.36(27.12~51.60)	34.23(25.36~43.09)	40.22(28.16~52.28)	0.152(0.126)	0.004** (0.460)	0.968(0.002)
	Unaffected side	59.63(45.88~73.37)	54.87(35.80~73.93)	59.45(44.69~74.21)			
MM	Affected side	22.90(15.91~29.90)	20.93(14.88~26.98)	21.20(13.95~28.46)	0.497(0.049)	0.001*** (0.588)	0.241(0.097)
	Unaffected side	29.91(21.43~38.39)	28.05(21.22~34.87)	32.17(24.19~40.15)			
LM	Affected side	44.72 (28.44–61.01)	43.05 (28.36–57.74)	46.28 (28.84–63.72)	0.202(0.108)	0.000*** (0.763)	0.950(0.004)
	Unaffected side	67.18 (46.94–87.42)	66.03 (51.10–80.96)	65.39 (56.26–74.51)			
MR	Affected side	54.76(42.16~67.36)	64.28(53.95~74.60)	73.40(60.49~86.31)	0.000*** (0.497)	0.051(0.245)	0.257(0.092)
	Unaffected side	66.26(49.83~82.69)	81.84(69.77~93.90)	77.76(65.30~90.21)			
LR	Affected side	48.21(34.43~62.00)	57.79(44.81~70.77)	64.38(50.83~77.93)	0.000*** (0.532)	0.003** (0.474)	0.567(0.040)
	Unaffected side	73.90(56.06~91.74)	87.73(73.68~101.78)	87.07(75.59~98.55)			
EMG Activation Level							
TA @stance phase	Affected side	0.04(0.02~0.06)	0.04(0.02~0.05)	0.03(0.02~0.04)	0.312(0.070)	0.300(0.067)	0.670(0.025)
	Unaffected side	0.03(0.02~0.04)	0.03(0.02~0.04)	0.03(0.02~0.03)			
TA @swing phase	Affected side	0.06(0.04~0.09)	0.06(0.04~0.08)	0.05(0.04~0.07)	0.137(0.117)	0.404(0.044)	0.569(0.035)
	Unaffected side	0.05(0.03~0.06)	0.04(0.02~0.06)	0.04(0.03~0.05)			
GL @stance phase	Affected side	0.07(0.05~0.10)	0.06(0.04~0.08)	0.06(0.04~0.08)	0.529(0.039)	0.918(0.001)	0.615(0.030)
	Unaffected side	0.06(0.05~0.08)	0.05(0.03~0.06)	0.06(0.04~0.08)			
GL @swing phase	Affected side	0.04(0.02~0.05)	0.04(0.02~0.05)	0.04(0.02~0.06)	0.171(0.104)	0.072(0.188)	0.729(0.020)
	Unaffected side	0.02(0.02~0.03)	0.02(0.01~0.03)	0.02(0.01~0.03)			

VMO @stance phase	Affected side	0.07(0.04~0.10)	0.07(0.04~0.09)	0.06(0.04~0.09)	0.282(0.076)	0.060(0.204)	0.301(0.072)
	Unaffected side	0.07(0.05~0.09)	0.06(0.05~0.08)	0.07(0.05~0.09)			
VMO @swing phase	Affected side	0.04(0.02~0.05)	0.04(0.02~0.06)	0.03(0.01~0.05)	0.670(0.025)	0.005^{**}(0.396)	0.806(0.013)
	Unaffected side	0.02(0.01~0.03)	0.02(0.01~0.02)	0.02(0.01~0.02)			
BF @stance phase	Affected side	0.09(0.07~0.11)	0.08(0.06~0.10)	0.08(0.07~0.10)	0.310(0.071)	0.029^{*}(0.265)	0.115(.127)
	Unaffected side	0.07(0.05~0.09)	0.06(0.05~0.07)	0.07(0.05~0.09)			
BF @swing phase	Affected side	0.07(0.04~0.09)	0.04(0.03~0.06)	0.05(0.04~0.06)	0.016^{*}(0.228)	0.041^{*}(0.235)	0.168(0.106)
	Unaffected side	0.04(0.03~0.06)	0.03(0.02~0.03)	0.04(0.03~0.05)			

The superscript "*" denotes a significant difference. One superscript indicates $p \leq 0.05$, two superscripts indicate $p \leq 0.01$, and three superscripts indicate $p \leq 0.001$.

2.5 Discussion

This study introduced an innovative Io-ENMS-assisted framework, which integrates the IoT and AF-ENMS, to support the safety, adherence, and efficacy of RAGT for post-stroke telerehabilitation. A pilot study with 16 stroke survivors validated the framework's feasibility in home environments, demonstrating high adherence and satisfaction. Following the telerehabilitation program, participants demonstrated significant gait restoration, as corroborated by clinical scores, gait analysis, and muscle activation patterns. The Io-ENMS-assisted framework effectively facilitated remote management and, for the first time, quantitatively characterized participant needs and therapist roles during telerehabilitation. Safety control and comparison with previous in-person training were also discussed in the end.

2.5.1 Feasibility of the Io-ENMS-assisted telerehabilitation

The telerehabilitation protocol offered a flexible training dosage, allowing participants to choose a daily training duration between 45 and 90 minutes and to distribute the session into multiple shorter periods. This flexibility was intended to prevent fatigue and enhance engagement [48]. Consequently, many participants frequently exceeded the 45-minute minimum (Figure 2.6A), with some completing up to seven periods per day, demonstrating high engagement with the home-based RAGT. The tele-program's feasibility is further supported by a significant decrease in the percentage of imbalanced steps out of total steps throughout the 20-session program (Figure 2.6A), indicating that participants effectively adapted to the self-help ENMS-assisted gait training and improved their balance during dynamic walking. Furthermore, participants reported high usability and satisfaction with the AF-ENMS, with USE subscale scores averaging approximately 80% (Table 2.4). This positive feedback, consistent across all education levels, including the 12 participants without a bachelor's degree, highlights the ease of learning and operation. Participants also found home-based training to be more enjoyable and motivating than conventional laboratory-based sessions, as indicated by higher scores in the interest/enjoyment subscale of the IMI (Table 2.4). This was likely due to the greater flexibility in training time and locations under effective management, allowing them to train in familiar environments and during preferred time slots (e.g., 7:00-9:00 and 18:00-20:00) that are often unavailable in conventional settings. One

adverse event was reported, where a participant exceeded the 90-minute daily training limit for two consecutive days, developing leg pain near the NMES application site. The administrative platform detected this deviation and alerted the PT (Figure 2.1C). Although the therapist resolved the symptoms, the participant withdrew from the study.

2.5.2 Effectiveness of the RAGT telerehabilitation program

After the telerehabilitation program, the participants achieved significant and lasting motor restoration in the lower limb, as indicated by the FMA-LE (Figure 2.7). Significant improvements were also noted in the BBS following the training and at 3MFU (Figure 2.7), suggesting better performance in various aspects of static and dynamic balance. Significant improvements in the FAC after the training and at 3MFU (Figure 2.7) indicated that participants were more confident about their functional ambulation on both level and non-level surfaces. These findings demonstrate that the program effectively improved walking ability in post-stroke participants.

Kinematic evaluations revealed significant improvements in gait patterns. The AF-ENMS was specifically designed for effective neurorehabilitation of distal joint impairments, i.e., foot drop and inversion [43]. After the AF-ENMS-assisted gait training, the primary kinematic outcomes, swing-phase ankle dorsiflexion and stance-phase foot inversion angles on the affected side, were significantly improved after the training (Figure 2.7). The improved voluntary motion of ankle dorsiflexion may be due to NMES to the TA muscle during dynamic gait cycles, which enhances intrinsic motor

performance. The reduction of voluntary ankle inversion may be attributed to two factors: (1) the musculoskeleton to stabilize the ankle during the stance phase, (2) the vibrotactile indicator to remind self-correction of medial-lateral plantar imbalance. However, improved ankle dorsiflexion angle was not maintained at 3MFU (Figure 2.7), possibly suggesting a need for higher training intensity for sustained gait pattern improvements [83]. Improvements in swing-phase knee flexion angle on the affected side were maintained at 3MFU (Figure 2.7), potentially due to enhanced distal joint control [84]. After stroke, abnormal gait patterns often develop from compensatory strategies adopted to regain walking ability quickly because of a limited hospital stay in the early stage after stroke. For example, circumduction gait is a common compensation for foot drop and inversion [85], involving increased hip abduction and decreased knee flexion to clear the foot and prevent falls. The improvement in knee flexion angle supports that intervention to the distal joints could contribute to kinematic improvements in multi-joints and a reduction in compensatory movements. These findings align with current guidelines for walking training after stroke, which increasingly emphasize both walking independence and quality [86], as compensatory movements can lead to increased energy costs and functional deficits [87].

Restoration of walking speed is a common primary outcome in lower limb training studies and suggests functional recovery [88]. Following this program, participants initially showed significantly decreased walking speed after the training (Figure 2.7),

which may be a consequence of participants prioritizing gait pattern relearning over velocity during AF-ENMS-assisted gait training. Speed subsequently increased by the 3MFU (Figure 2.7), confirming that the program did not negatively impact long-term ambulation. This result is consistent with the 10MWT, which also shows no improvement in walking speed after the training. Gait asymmetry correlates with increased energy expenditure and is a significant predictor of post-stroke falls [89]. In this program, participants demonstrated improved gait symmetry, as evidenced by prolonged swing time on the unaffected limb and reduced step length on the affected side (Figure 2.7). The decreased differences in step length between both limbs at 3MFU further supported the improved bilateral locomotion symmetry (Figure 2.7). Concurrently, the peak pressure under the rearfoot, i.e., LR and MR on both sides, significantly increased after the training (Figure 2.7), suggesting a shift towards a more normative foot-strike pattern [90]. Although increased MR after the training was associated with significant difference between both limbs, this difference disappeared at 3MFU (Figure 2.7), indicating improved symmetry in loading pressure over the long term. Finally, participants showed a reduction in abnormal activation patterns in the GL muscle on the unaffected side and the BF muscle on the affected side following the training (Figure 2.7), suggesting a normalization of the motor control of both sides [91]. While this reduction in the BF muscle was not sustained at 3MFU, it was associated with a lasting reduction in muscle activation asymmetry between both limbs at 3MFU (Figure 2.7).

2.5.3 Client demands in telerehabilitation management

The hybrid tele-management mode effectively addressed participants' diverse needs during the tele-program. Most logistical and technical issues were resolved through remote communication, with in-person home visits reserved for critical issues. The online chat groups served as the backbone of our daily tele-management, offering flexibility and continuity that allowed participants to ask questions and report progress at their convenience, while therapists could review and respond efficiently between sessions [92]. All group chat logs were recorded and analyzed to examine interactions between paired patients and therapists in terms of message topics and types. As expected, a significant portion of messages focused on training management, with patient and PT messages accounting for 60.49% and 62.65%, respectively (Table 2.3). These interactions confirm that the chat group fulfilled its intended role in routine management, including monitoring, guidance, adjustment, and encouragement, consistent with therapist functions identified in prior telerehabilitation studies [29]. The chat group also provided a convenient medium for various message types. For example, participants shared 644 image messages, including screenshots of the app and pictures of the AF-ENMS, and 95 video messages related to training, which allowed therapists to promptly monitor training performance.

Beyond management, the chat group also fostered social interaction. Over the 20-session program, non-program-related messages accounted for 26.59% of patient

messages and 20.11% of PT messages (Table 2.3). This indicates participants' latent social needs during telerehabilitation. Post-training interviews confirmed that the online group created a valuable peer-support space to share experiences and build connections. This social dimension is particularly important, as telerehabilitation inherently reduces direct human contact and peer interaction compared with clinic settings. Moreover, stroke survivors often perceive a profound lack of social connection stemming from functional impairments that limit their participation in daily life, in accordance with the International Classification of Functioning, Disability and Health framework [93]. Social incentives, defined here as factors that encourage individuals to modify their behavior in response to social relationships or connections [59], are well-documented in health behavior change and can be harnessed in telerehabilitation programs as a scalable, cost-effective means of enhancing participant engagement. In our framework, the online chat group functioned not only as a management tool but also as a community for paired stroke survivors, embedding social incentives into the telerehabilitation experience. Analysis revealed a moderate positive correlation between training duration and the proportion of both training-related and non-program-related messages, suggesting an association between social interaction and training engagement. These findings underscore the importance of telerehabilitation systems to support both routine therapist functions and the development of peer communities, thereby promoting engagement while minimizing demands on clinical resources. In this trial, a minimal community consisting of two patients and a therapist was implemented. Future studies

could include additional patients in the training community while carefully maintaining a balance between training management and social interaction.

2.5.4 Safety control within telerehabilitation

Safety control is a multifaceted challenge for RAGT in home environments. Unlike upper limb training, where stroke patients attend RAT while seated in a stabilized position [67], RAGT requires stroke patients to use wearable robots and perform locomotion over larger areas with dynamic balance control. In this program, several methods were adopted to achieve safety control. Firstly, well-designed robot and thorough preparation were provided for the telerehabilitation program. The AF-ENMS is lightweight and is suitable for self-help operation [43], and the App emphasizes user-friendliness, with large-font instructions, explicit menu architectures, and streamlined navigation to support self-help operation. Before home-based training, a tutorial and three guided sessions, which have been shown to be adequate for both robot-assisted upper limb and gait training [43, 67], were followed by a final competency test (Table 2.1) to ensure participants' ability to conduct RAGT safely without close supervision from therapists. While technology literacy at the client's end has been argued as a barrier to telerehabilitation [94], our high USE scores (Table 2.4) and the fact that participants of all education levels completed the training without additional guided sessions demonstrate the accessibility of AF-ENMS-assisted gait training.

Due to limited home space in Hong Kong, many participants conduct RAGT in public

areas, which easily raises safety concerns from the environment and unexpected disturbance. Therapists therefore observed each participant's home environment and its vicinity, and helped select at least two suitable routes for training, including locations at home, parks, corridors, quiet streets, and shared community clubhouses, to ensure continuity of training. During the program, participants sometimes reported challenges such as slippery surfaces, strong sunlight, or crowded areas, and they used the program's flexibility to adjust training times or routes accordingly. No participant violated the training protocol due to disruptions in the training routes. Additionally, weekly videoconferencing was conducted to ensure the safety of training for each participant and promptly resolve issues (Table 2.2). For example, two participants reported that their proportion of imbalanced steps remained at 100%. Therapists provided seven video conferences, including the weekly checklists, to deliver guidance and conducted two home visits to rule out technical issues. It was concluded that the issue stemmed from ankle inversion and was not fully resolved by the end of the training. However, their ankle inversion did decrease, and no adverse events occurred under the supervision of their caregivers.

Despite these safety measures, concerns about uncontrolled RAGT in home environments remain, as walking training is typically conducted under full supervision from therapists or caregivers to prevent adverse events. Evidence from prior research suggests that caregiver requirements for home-based RAGT depend on factors such as

device design, patient selection, and supervision methods [95]. For example, in a device-assisted telerehabilitation study during COVID-19 [96], safety precautions were provided through pre-training teleconferencing; however, a care partner was required for all treatments because the device intentionally induced subtle destabilization of the nonparetic side. In contrast, another study using RAGT did not require caregiver presence because the device was demonstrated to be stable and smooth to support knee motion similar to biological mechanics [78]. Some other studies requiring no caregiver presence used live warning systems to stop exercises when unsafe conditions are detected [95]. In our study, five participants completed the program independently and experienced no adverse events, as all met the criterion for sufficient functional ambulation (FAC$\geqslant$4). In addition to the much attention to external safety controls, participant behavior must be regulated, as evidenced by the earlier-mentioned adverse event related to overtraining. This underscores the need for more comprehensive safety management in future home-based RAGT programs, which could include automatic shutdown mechanisms to prevent deviations from prescribed training protocols.

2.5.5 Comparison with in-person training

This study represents the first implementation of AF-ENMS-assisted gait training in a home environment. Previously, a pilot study reported the rehabilitative effectiveness of a 20-session AF-ENMS-assisted gait training program with close, in-person supervision [43]. The two studies both showed significant and lasting improvements in

lower limb motor function and balance, as indicated by the FMA-LE and BBS. Interestingly, a significant improvement in the FAC was only observed in this study after the training and at 3MFU (Figure 2.7), indicating that participants were more confident in functional ambulation. This may be attributed to the fact that participants were trained in familiar home environments, which facilitated the transfer of acquired motor skills to daily walking contexts [97]. However, compared with the in-person study [43], this study observed smaller gains in the FMA-LE and a nonsignificant change in ankle spasticity (Figure 2.7). RAGT naturally involves balance control and weight-shifting tasks, closely associated with the BBS improvements commonly reported in other RAGT studies [98]. These discrepancies suggest that the effect on fine motor control may be limited compared with in-person rehabilitation. Possible reasons might be that in-person sessions allowed therapists to continuously optimize stimulation parameters and provided direct feedback for gait training [99], whereas the home-based training relied primarily on patient self-report and asynchronous therapist review. Integration of adaptive stimulation algorithms and real-time feedback systems into the telerehabilitation system may help close this performance gap. Nevertheless, differences in training protocols and participant baseline characteristics limit the accuracy of these cross-study comparisons. A future randomized controlled trial (RCT) with a larger sample size is needed for head-to-head evaluation.

The telerehabilitation program greatly reduced time burdens for healthcare providers

compared with in-person training. In this study, the time burden for therapists stemmed from two phases: pre-training preparation and ongoing remote management. Before training, a tutorial lasting 30 to 45 minutes and three guided sessions, each lasting about an hour, were provided. After starting home-based training, the primary time burden shifted to remote management, including responses in online groups, videoconferences, and home visits. Based on logs of remote communication, the estimated remote time for each participant was around 84 minutes during the 17-session home-based training. Home visits, while less frequent, were significantly more time-consuming due to round-trips, which is also a common complaint and a major expense in traditional in-person rehabilitation. In comparison, the time commitment for therapists was remarkably higher for in-person training, where each one-hour session required full, on-site supervision. While the total costs between the two settings were not fully calculated as the service was not yet in routine clinical use, they could be estimated based on therapist time, travel expenses for round-trips, and the rental cost of AF-ENMS devices. A previous study [100] concluded that the cost of delivering in-person therapy significantly exceeds that of telerehabilitation in terms of human resources, round-trips, and instrumentation when using the same VR-based training. As both therapists and patients become more proficient with the technology, the time and costs spent on training guidance and troubleshooting are expected to decrease further.

2.6 Periodic summary

Chapter 2 introduced a novel Io-ENMS system that integrates IoT technology with AF-ENMS to support post-stroke robot-assisted telerehabilitation and tele-management. This system enabled remote supervision by PT, facilitated cyber interactions among paired stroke users during their rehabilitation, and allowed for management of training progress via a digital network. In a single-group trial, participants with chronic stroke (n=16) were recruited to complete a program consisting of 20 sessions of RAGT in home environments based on this system. The results confirmed the feasibility of the system, which was supported by high participant engagement, smooth management, perceived usability, and satisfaction. Its effects in improving lower-limb motor function and gait patterns were also demonstrated after the training and at 3MFU. Moreover, the study first provided quantitative results for client needs throughout the telerehabilitation program and discussed the implementation of safety controls for future telerehabilitation studies.

CHAPTER 3

TRANSLATION OF EXONEUROMUSCULOSKELETON-ASSISTED WRIST-HAND TELEREHABILITATION FROM LABORATORY TO CLINICAL SERVICE AFTER STROKE

3.1 Introduction

The demand for self-help, home-based telerehabilitation has surged following global disruptions, such as the COVID-19 pandemic, which highlighted the limitations of traditional, center-based outpatient services. Motor recovery of wrist and hand function presents a particularly formidable challenge in post-stroke rehabilitation. The distal upper limb typically exhibits a delayed recovery compared to proximal joints, yet hospital stays are often insufficient due to constraints on inpatient beds and professional staff [24, 101]. This deficiency underscores the critical need for effective home-based solutions for extensive, repetitive, and intensive physical training.

While various technologies like virtual reality [102] and robots are used to supplement traditional therapy, robots are especially useful for providing the intensive physical training needed to assist paralyzed limbs with the required torque [103]. However, most clinically effective robots are large, institution-based systems that require professional operation [104]. Although some lighter, soft robotic systems have been developed for home use [105, 106], they have faced significant obstacles. For example, to ensure

safety for non-professional users at home, the power and mechanical assistance of these devices are often reduced [107], which can compromise their effectiveness in promoting VMEs crucial for neuroplasticity and long-term recovery. These devices may also fail to prevent compensatory shoulder and elbow movements, which can lead to learned disuse of the wrist and hand [108]. The successful implementation of research-proven rehabilitation protocols into real-world clinical practice is difficult. For example, therapists in clinical settings may adapt protocols based on their own habits, deviating from the strict research guidelines [109]. Telerehabilitation, where patients train at home with remote supervision, introduces additional complexities, including a patient's readiness for independent training and a therapist's ability to provide timely remote support [42].

Previous work from our group introduced a mobile ENMS aimed at supporting upper-limb rehabilitation [32], a system that is now available commercially (Thecon Technology (HK) Limited, Hong Kong, P.R. China) (Figure 3.1). The design incorporates EMG signals to actively detect and amplify VMEs at the elbow, wrist, and hand [110]. By coupling NMES with pneumatic actuation, the device delivers both NMES and mechanical assistance. This integrated approach has been reported to foster more effective muscle coordination, limit compensatory movements, and accelerate functional recovery compared with interventions that rely solely on mechanical or electrical stimulation [111-113]. In a pilot trial, the wrist-hand module of the ENMS

(WH-ENMS) proved its effectiveness for motor rehabilitation in an on-site, professionally assisted setting [32]. Building on these studies, a follow-up trial study explored its use in self-help, home-based telerehabilitation [35]; participants, with or without assistance from caregivers, were able to operate the device, maintain compliance with the regimen, and achieve notable improvements in motor performance, with no safety concerns observed [35].

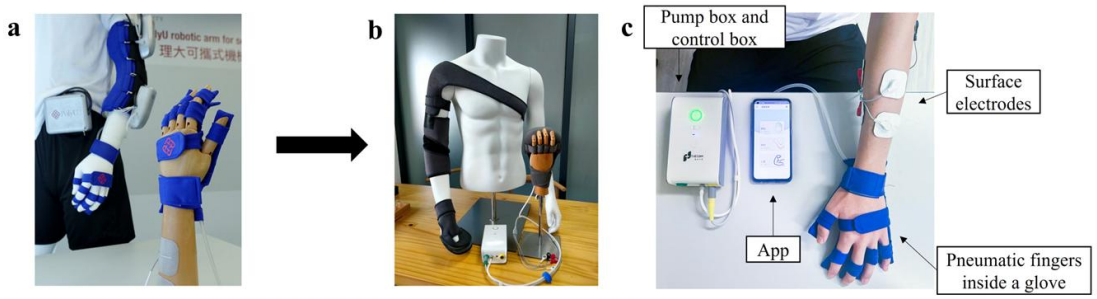

Figure 3.1 Progression of upper limb ENMS from laboratory research to commercial deployment. (**a**) Prototype version of ENMS created in the laboratory; (**b**) commercially released version of ENMS; (**c**) the wrist-hand module of ENMS used in the study.

3.2 Study aims

The present study implemented the self-help telerehabilitation program assisted by WH-ENMS in a publicly operated rehabilitation center. The study aimed to examine the feasibility of integrating this telerehabilitation program into routine clinical workflows and to compare training outcomes between the research-driven training and its application in a real-world service context, using a non-randomized trial design.

3.3 Methods

3.3.1 WH-ENMS

The WH-ENMS is a lightweight (45g wearable component) system that facilitates wrist-hand rehabilitation. It utilizes a combination of pneumatic actuation and NMES, both triggered by residual EMG signals from a stroke survivor's paretic muscles. The device assists two movements: wrist extension coupled with hand opening, and wrist flexion with hand closure [35]. The operation of ENMS is managed through a smartphone-based mobile App, which links to the device's control unit wirelessly via Bluetooth. Assistance is triggered by an EMG-based control algorithm that activates support once the user's VME surpasses a defined threshold, set at three SDs above baseline EMG activity [32]. EMG signals are captured from two muscle pairs: the extensor carpi ulnaris (ECU) and extensor digitorum (ED) for extension movements, and the flexor carpi radialis (FCR) together with the flexor digitorum (FD) for flexion movements [35]. The system employs two EMG-NMES channels, allowing simultaneous signal detection and stimulation delivery through reusable surface electrodes positioned at the common motor points of these muscles [32]. This electrode configuration has been validated in earlier studies as both reliable for control [32] and suitable for independent use [35]. To reduce electrical noise, a reference electrode is attached to the olecranon, and skin markings are provided to assist with accurate electrode placement.

3.3.2 Translation of the telerehabilitation program

The telerehabilitation program comprised 20 WH-ENMS-assisted sessions over seven consecutive weeks, with an intensity of three to five sessions per week [35]. The first three sessions, along with an initial tutorial, were designated as mandatory courses conducted under onsite professional supervision for both the patient and their caregivers. Following these initial sessions, subsequent home-based sessions were remotely supervised by a professional who monitored the patient's progress using automated feedback from the WH-ENMS, such as training duration and task repetitions.

In our earlier work, the program was tested within a controlled laboratory setting with continuous researcher supervision [35]. In this study, it was implemented at the Community Rehabilitation Service Support Centre (CRSSC) under the Hospital Authority of Hong Kong. To facilitate this transition, our team delivered a two-hour orientation session to the CRSSC staff, which comprised an occupational therapist (OT), an occupational therapy assistant (OTA), and a clinical engineer (CE). The session introduced the intervention protocol, outlined implementation steps, and addressed practical considerations for service delivery. Within this arrangement, the OT and OTA assumed responsibility for patient-facing activities, whereas the CE oversaw technical upkeep of the system. The technical translation of the program to the CRSSC involved training the clinical team on WH-ENMS configuration for individual patients, designing and implementing upper limb tasks, and developing remote supervision skills

for home-based training. Two WH-ENMS systems were provided to the CRSSC, allowing the OT and OTA to integrate the training into their regular working hours and conduct parallel sessions.

3.3.3 WH-ENMS-assisted self-help telerehabilitation program

The study employed a non-randomized trial design, and participant progression was illustrated using a CONSORT flow diagram (Figure 3.2). Before initiating the trial, ethical clearance was obtained from the institutional review boards of both The Hong Kong Polytechnic University and the Research Ethics Committee of Kowloon Central and Kowloon East. All subjects provided documented informed consent before undergoing any study procedures.

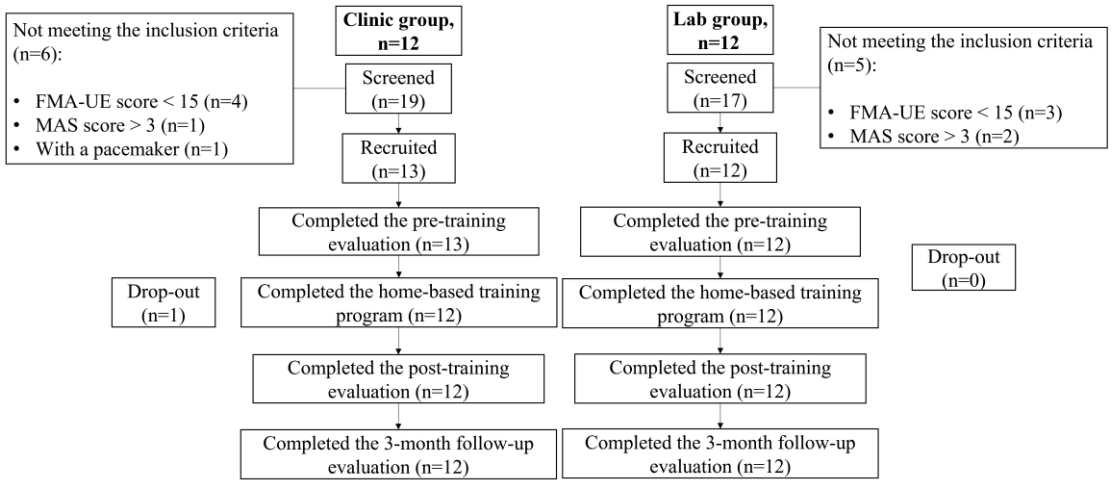

Figure 3.2 CONSORT flow diagram of the study.

3.3.3.1 Participant recruitment

Participants were recruited from two distinct settings: (1) Clinic group: outpatients with

stroke receiving care at the CRSSC were screened and enrolled to receive the training in a clinical environment. (2) Lab group: stroke patients from the local community were screened and recruited to complete the training in the university's neurorehabilitation engineering lab.

Inclusion criteria for the two groups were as follows: (1) history of a single, unilateral stroke occurring more than 12 months prior to enrollment; (2) MAS score below 3 for upper limb spasticity (elbow, wrist, and finger) [114]; (3) Fugl-Meyer Assessment for Upper Extremity (FMA-UE) score exceeding 15 [115]; (4) MMSE score greater than 21 [116]; (5) detectable voluntary EMG activities (≥ 3 SD above resting baseline) in the driving muscles (ECU-ED and FCR-FD) on the paretic side; (6) Functional Independence Measure (FIM) score of 51 or higher; and (7) fulfillment of basic home environmental requirements, including a stationary chair, a table providing a usable surface of at least 60 cm in length and 40 cm in width, and access to a 3G or faster mobile network.

Exclusion criteria consisted of: (1) epilepsy; (2) presence of cardiac pacemakers or implanted electronic medical devices; (3) cutaneous lesions or open wounds in electrode placement regions; (4) acute inflammatory conditions; (5) significant shoulder or central post-stroke pain; (6) comorbid neurological disorders unrelated to stroke; or (7) if they were concurrently receiving other upper limb treatments during the telerehabilitation program.

3.3.3.2 Intervention protocol

All participants from both groups adhered to the same telerehabilitation program assisted by WH-ENMS (Figure 3.3). The program was delivered through two phases, beginning with supervised mandatory sessions held at either the CRSSC or the university laboratory, and transitioning to self-help home-based training sessions. The mandatory courses included a pre-training tutorial and three guided training sessions.

Figure 3.3 Timeline and configuration of the 20-session training program. (**a**) Program timeline; (**b**) OT/OTA guided sessions at the CRSSC; (**c**) Researcher guided sessions in

the lab. The repetitive limb tasks in each session included (**d**) a horizontal task and (**e**) a vertical task for both groups, and (**f**) an optional forward task available at the CRSSC.

Pre-Training Tutorial

Before the program began, each participant and any assisting caregivers were given a tutorial covering the proper donning and doffing of the system, operation of the mobile App, and the training protocols. Individualized training parameters, including EMG threshold level, NMES intensity, and mechanical assistance level, were configured at this stage and remained fixed for the duration of all 20 sessions, as detailed in [35]. For participants without a personal smartphone, a smartphone was loaned to them for the duration of the study.

Training Protocol in Sessions

Each training session consisted of repetitive limb tasks, interspersed with 10-minute rest intervals to mitigate muscular fatigue. Participants were positioned seated at a table with their shoulder height maintained 30-40 cm above the work surface. A smartphone displaying the training app was placed 30-60 cm in front of the participant to provide visual cues. The repetitive limb tasks included a horizontal task and a vertical task. In the horizontal task, the participant gripped a sponge (8.5 × 5.5 cm^2) from the affected side, released it 50 cm laterally on the opposite side, and then returned it to the original, marked position. The vertical limb task involved grasping a sponge from beneath an 18 cm elevated shelf, relocating it to the top surface, and then returning it to the original

location.

The initial three guided training sessions, led by study operators, featured a progressive assistance model: (1) fully assisted: in the first session, operators provided full support, from setting up the training to supervising the entire process. (2) semi-assisted: the second session required participants to complete the tasks primarily on their own, with only minimal assistance from the operators. (3) independent-with-Observation: during the third session, participants performed the training independently while being closely observed by the operators. Individuals who had not achieved readiness for this level following the second session received an additional semi-assisted session. Once the operators determined a participant was competent for self-help training, they proceeded with the remainder of the sessions in a home-based setting. During the guided sessions, operator feedback was directive in nature, emphasizing specific corrective guidance to facilitate effective transition to independent training.

For the initial self-help session, an experimental operator visited each participant's residence to deliver the WH-ENMS, its charging equipment, and the required training materials (sponge and shelf). During this visit, the operator also inspected the home environment for safety and observed a full training session to ensure the participant's execution was consistent with the guided sessions. Feedback during subsequent self-help sessions was more descriptive, aimed at resolving any technical issues and understanding the participant's overall experiences. The frequency and detail of this

feedback were adapted based on each participant's unique needs and progress.

Management of home-based self-training

Training data, comprising session frequency, duration, and the number of completed movement cycles, were automatically logged by the App and uploaded via mobile network to a server at the neurorehabilitation laboratory. In the two groups, operators tele-monitored the data according to a training schedule prearranged with each participant. If a session was missed, the operators would contact the participant via phone or text message to schedule a make-up session, which was conducted in strict accordance with standardized protocol requirements. In the event of a technical issue, participants were required to report it immediately. A backup system, stored at the CRSSC or the lab, was prepared for each participant and could be replaced within one business day to avoid disruption to the training protocol. Additionally, operators maintained weekly contact with participants through phone calls or messages to discuss their experiences and provide ongoing support.

3.3.3.3 Clinic group versus lab group

While both groups received the same telerehabilitation program, some variations existed, primarily in the roles of the experimental operators, the training environment, and the specific intervention protocols. Table 3.1 provides a comparative summary of these variations. For the lab group, a researcher specializing in neurorehabilitation engineering delivered the intervention. All mandatory sessions took place in a dedicated

area of the university's neurorehabilitation laboratory, commencing three days following the initial tutorial. During these supervised sessions, the operator provided immediate verbal feedback to correct compensatory strategies, such as excessive trunk sway during reaching tasks. They consistently reminded participants to minimize these actions to promote effective motor recovery. For the self-help phase, participants had access to 24-hour support via hotlines and instant messaging channels, and no training fees were charged.

In contrast, operators for the clinic group consisted of a registered OT and an OTA from the CRSSC. Mandatory sessions were held in a private training room at the clinic, where operator supervision was limited to approximately 30 minutes during both guided and initial self-help sessions. This was a necessary compromise due to the CRSSC's need for therapists to manage multiple patients simultaneously. Once an operator determined a participant could perform the tasks independently, they were free to attend to another patient. Furthermore, operators in the clinic group were given more flexibility to adapt the protocol based on their clinical experience and the principles of task-oriented rehabilitation. For example, they were allowed to use various grasping objects, such as a plastic apple or cup, to simulate real-world tasks. More significantly, unlike the lab group, operators in the clinic group allowed task completion even with compensatory movements, viewing these as a form of functional restoration [117]. An optional forward task, which involved gripping an object and moving it 30 cm forward,

was also integrated into each session, extending the total session duration to between 60 and 90 minutes. Participants in the clinic group were charged a fee of HKD 375 for the mandatory courses, which was part of the CRSSC's routine administrative procedure.

Table 3.1 Comparison of trial implementation between the two groups.

	Clinic Group	**Lab Group**
Participants source	Outpatients referred by rehabilitation doctors	Volunteers from local communities
Evaluation		
Venue	Neurorehabilitation lab at PolyU	
Assessor	The same blinded assessor	
Mandatory courses		
Venue	A treatment room, CRSSC	Neurorehabilitation lab at PolyU
Operator	Registered OT, OTA	Research staff
Supervision duration	The first 30 min/session	60 min
Self-help training		
Venue	Participants' homes	
Training frequency	3–5 sessions/week	
Session duration	60–90 min/session	60 min/session
Remote training supervisor and contact	Registered OT	Research staff
Remote availability	9 am to 6 pm, Monday to Friday	Flexible whenever needed
Withdrawal	Yes, at any time point in the program	
System Maintenance	Referred by the CE to technicians of the research team	Technicians of the research team
Charge to patient	HKD375 at the CRSSC	Free

3.3.4 Measurements of training outcomes

Participants in both the clinic and lab groups underwent clinical assessments at three time points: pre-training evaluation conducted before the tutorial, post-training evaluation the day after the final session, and 3MFU evaluation. To establish a stable baseline, the pre-training evaluation was performed three times within two weeks,

ensuring a minimum of two days elapsed between consecutive sessions. The mean score of these three baseline assessments was utilized for all subsequent statistical analyses. EMG and kinematic assessments, which provided quantitative data on muscular coordination and movement performance, were administered both before and after the training intervention. The FMA-UE served as the primary outcome measure in this study. All additional clinical scales, along with EMG recordings and kinematic variables, were designated as secondary outcomes. A customized questionnaire was also administered to assess participants' experiences regarding program usability and their motivation during the self-help training.

3.3.4.1 Clinical assessments

All clinical evaluations in the two groups were performed by an assessor blind to both the study protocol and group assignments. The following standardized clinical measures were used: (1) FMA-UE: This is widely recognized for its reliability in detecting motor function improvements, and is divided into a 42-point section for shoulder and elbow function, i.e., FMA shoulder/elbow, and a 24-point section for wrist and hand function, i.e., FMA wrist/hand [115]. (2) Action Research Arm Test (ARAT): This test comprises 19 questions and measures both proximal and distal arm motor function, with a total score of 57 points [118, 119]. (3) FIM: An ordinal instrument designed to quantify disability levels in ADL [120]. (4) Wolf Motor Function Test (WMFT): This test comprises 17 functional tasks and evaluates upper limb motor

performance based on the time of execution [121]. (5) MAS: This is the most common scale for assessing muscle tone and was utilized to evaluate spasticity in the elbow, wrist, and finger flexors [114, 122].

3.3.4.2 EMG evaluation

To quantitatively evaluate muscular activation and coordination, EMG recordings were obtained from five muscles of the affected upper limb, including abductor pollicis brevis (APB), triceps brachii (TRI), biceps brachii (BIC), ECU–ED, and FCR–FD. Each EMG session began with measurement of MVCs for each target muscle. Subsequently, participants performed three repetitions of the horizontal and vertical tasks employed in training under a bare-arm condition, without the use of the WH-ENMS device, as detailed in [35]. A two-minute rest period was enforced between trials to mitigate the effects of muscular fatigue. The same tasks were adopted for both training and evaluation because (1) the reach-grasp-release is one of the most fundamental and commonly performed upper-limb functional tasks, and (2) using the same tasks allowed us to effectively track changes in muscle coordination and kinematic performance over the course of recovery, as demonstrated in our robot-assisted upper-limb training protocol. Raw EMG signals were amplified, band-pass filtered (10–500 Hz), and digitized at a sampling rate of 1000 Hz. Analysis focused on two primary EMG metrics: the normalized activation level of individual muscles, and the co-contraction index (CI) for relevant muscle pairs [81].

For muscle i, the activation level was calculated as an average normalized value with respect to its maximum value during MVCs. It was obtained by first calculating,

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

Here, $EMG_i(t)$ was the mean rectified amplitude envelope following application of a 10 Hz filtered low-pass fourth-order Butterworth filter. Then, EMG was normalized by

$$EMG_i = \frac{\overline{EMG} - \overline{EMG}_{rest}}{\overline{EMG}_{MVC} - \overline{EMG}_{rest}},$$

Here $\overline{EMG}_{rest}$ was the baseline EMG level at rest, and $\overline{EMG}_{MVC}$ was the maximum value obtained from MVCs. The EMG CI measured the independence of muscle pairs [81] and was computed for all possible combinations of the recorded muscles (FCR-FD, ECU-ED, APB, TRI, and BIC):

$$CI = \frac{1}{T}\int_0^T A_{ij}(t)dt,$$

In this formula, $A_{ij}(t)$ represented the overlapping area of the EMG activity envelopes of the muscle i and muscle j. A higher CI value indicates greater overlap and less independent muscle activity. A decrease in both EMG activation levels and CI values generally suggests reduced muscle tone and improved muscular coordination.

3.3.4.3 Kinematic evaluation

Kinematic measurements were performed using a Vicon motion capture system (Vicon

Motion Systems, Oxford, UK), with standard marker configuration on the upper limb and trunk [123]. These measurements were used to evaluate motion smoothness and compensatory body movements. Participants performed identical bare-arm assessment trials as those administered during the EMG evaluation, performing three repetitions of each task with a two-minute break between trials. Two parameters were used for this analysis: (1) number of movement units (NMUs) [124], which is a count of significant changes in the tangential velocity profile recorded at the metacarpophalangeal joint of the middle finger. A higher NMU count indicates less smooth movement; (2) maximal trunk displacement (MTD) [124], which quantifies the maximum displacement of the trunk in 3D space during a task, relative to its starting position. It serves as a measure of compensatory trunk movements.

3.3.4.4 Customized questionnaire

A two-part questionnaire was customized to measure participant experiences, drawing from the USE [71] and the IMI [125] questionnaires. Both parts used a seven-point Likert scale (1 to 7). The USE, previously used for RAT [73], assessed the program's usability across four dimensions: usefulness, ease of use, ease of learning, and satisfaction. Scores for each dimension were normalized by dividing the sum of item scores by the total possible score for that dimension [126]. A modified IMI questionnaire with 28 items was used to evaluate intrinsic motivation [76]. It was structured into seven distinct subscales: interest/enjoyment, perceived competence,

effort/importance, pressure/tension, perceived choice, value/usefulness, and relatedness. Subscale scores were calculated by averaging the items and then normalizing this average against the maximum possible scores [125].

3.3.5 Statistical analysis

All statistical procedures were conducted in SPSS software, version 26 (IBM, Chicago, IL, USA). Normality of all outcome variables was assessed using the Shapiro-Wilk test [125]. For clinical outcomes satisfying normality assumptions, one-way repeated measures ANOVA with Bonferroni-adjusted post hoc comparisons was employed to evaluate differences across baseline, post-intervention, and 3MFU assessments. Non-normally distributed clinical data were analyzed using the Friedman test, followed by Wilcoxon signed-rank tests for post hoc pairwise comparisons. Analysis of EMG and kinematic parameters utilized paired t-tests for normally distributed data and Wilcoxon signed-rank tests for non-parametric comparisons. Between-group differences in clinical scores at post-training and 3MFU were examined using Quade's Analysis of Covariance (ANCOVA), controlling for the average of the three baseline measurements as a covariate. Inter-group differences in changes in EMG, kinematic, and questionnaire outcomes were assessed with independent t-tests for parametric data and Mann-Whitney U tests for non-parametric alternatives. A threshold of $p \leq 0.05$ was applied for statistical significance, with additional levels of $p \leq 0.01$ and $p \leq 0.001$ also reported.

3.4 Results

Between April 2020 and December 2022, a total of 36 individuals were screened from the CRSSC and the local stroke community. Of these, 25 participants who met all requirements were admitted into the study. The CRSSC provided 19 outpatients, of whom 13 were admitted to the clinic group. Simultaneously, 17 individuals were screened in the local community, leading to the recruitment of 12 participants for the lab group. One participant allocated to the clinic group discontinued participation after five sessions for personal reasons. A final cohort of 24 participants completed the telerehabilitation program. As detailed in Table 3.2, demographic characteristics indicated no statistically significant intergroup differences ($p > 0.05$) in age, gender, hemiplegic side, or stroke type. However, a significant between-group difference ($p \leq 0.05$) was observed in time since stroke onset, with the lab group demonstrating a longer post-stroke duration compared to the clinic group.

Table 3.2 Demographic data of the participants for both groups.

Characteristics	Age [a] in years (mean ± SD)	Time since stroke [a] in years (mean ± SD)	Gender [b] (male/female)	Hemiplegic side [c] (left/right)	Stroke type [c] (ischemic/hemorrhagic)
Clinic group (n=12)	53.33 ± 11.47	3.32 ± 2.22	7/5	6/6	3/9
Lab group (n=12)	58.42 ± 13.47	12.42 ± 10.88	6/6	9/3	6/6
P	0.203	0.003*	0.682	0.400	0.400

[a] Mann–Whitney U test. [b] Pearson Chi-square test. [c] Fisher's exact test. The superscript "*" ($p \leq 0.05$) denotes a significant inter-group difference.

3.4.1 Behavioral improvements in clinical assessments

Pre-training clinical assessments indicated no statistically significant differences between the two groups across measured scores ($p > 0.05$), except for the FIM, where a significant inter-group difference was noted ($p \leq 0.05$). As shown in Figure 3.4, both groups exhibited significant post-training increases in FMA-UE, FMA shoulder/elbow, and FMA wrist/hand scores ($p \leq 0.05$). At 3MFU, enhancements in FMA-UE and FMA shoulder/elbow remained significant for both groups, whereas significant improvement in FMA wrist/hand was maintained exclusively in the lab group ($p \leq 0.05$). The lab group achieved significantly higher FMA-UE scores at 3MFU, as well as superior FMA wrist/hand scores at both post-training and 3MFU assessments, relative to the clinic group ($p \leq 0.05$). Both groups showed a significant improvement in ARAT scores post-training ($p \leq 0.05$), but only the lab group sustained this improvement at the 3MFU ($p \leq 0.05$). Similarly, both groups significantly increased their WMFT scores post-training, and these gains were maintained at the 3MFU ($p \leq 0.05$). However, only the lab group exhibited a significant reduction in WMFT time both post-intervention and at 3MFU assessment ($p \leq 0.05$). The lab group's post-training WMFT time was also significantly lower than that of the clinic group ($p \leq 0.05$). Spasticity, measured by the MAS, significantly decreased in the elbow, wrist, and finger joints for the two groups post-training ($p \leq 0.05$). These decreases in wrist and finger joints spasticity score remained statistically significant at the 3MFU ($p \leq 0.05$). For a complete breakdown of inter- and

intra-group comparisons in clinical scores, refer to Table 3.3.

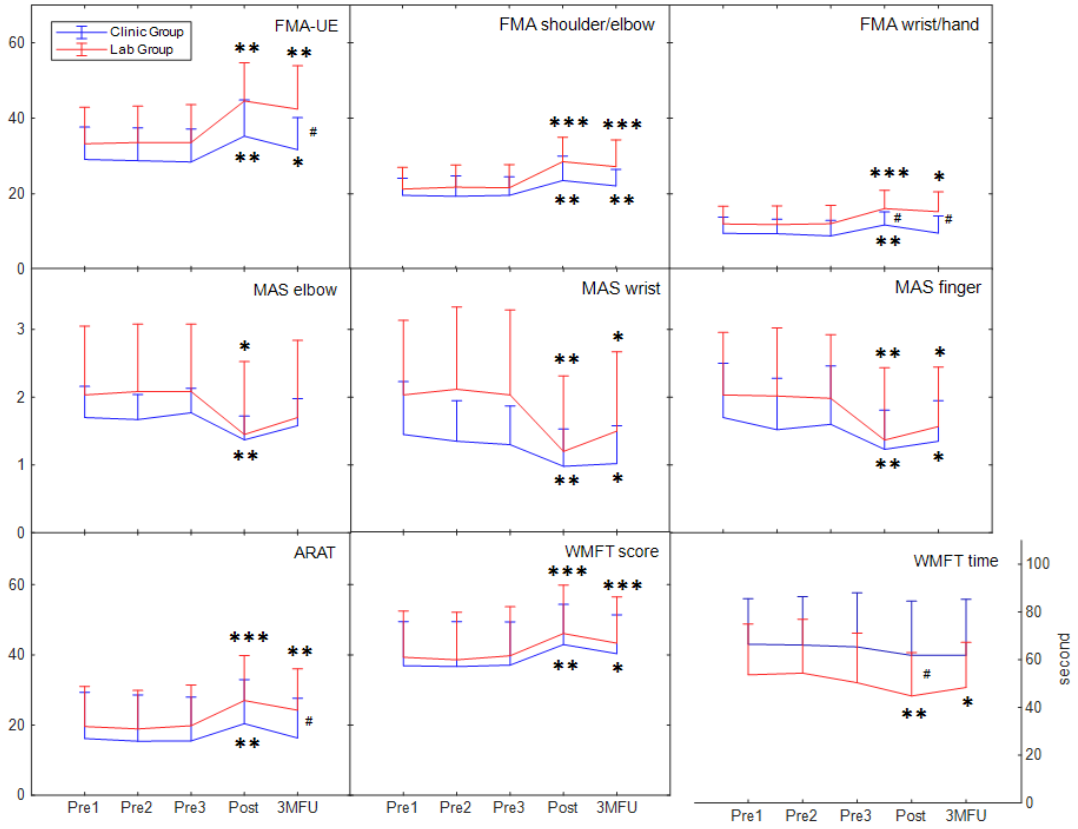

Figure 3.4 The clinical scores for behavioral improvements for both groups at pre-, post-, and 3MFU assessments. Data are shown as means ± SDs. The symbols "*" and "#" denote significant intragroup and intergroup differences, respectively. One symbol indicates $p \leq 0.05$, two symbols indicate $p \leq 0.01$, and three symbols indicate $p \leq 0.001$.

Table 3.3 The clinical scores for both groups at the pre-, post-, and 3MFU assessments.

Clinical Assessments	Group	Pre1	Pre2	Pre3	Post	3MFU	1-Way Repeated Measures ANOVA	Friedman Test	Quade's ANCOVA	
		Mean Value (95% Confidence Interval)					p (Partial η2)	p (Kendall's W)	p_{Post} (Partial η2)	p_{3MFU} (Partial η2)

FMA-UE	Clinic	29.08 (23.64~34.53)	28.75 (23.24~34.26)	28.42 (22.87~33.96)	35.25 (29.15~41.35)	31.67 (26.29~37.05)		<0.001 *** (0.771)	0.056 (0.156)	0.019 # (0.226)
	Lab	33.25 (27.11~39.39)	33.58 (27.48~39.69)	33.58 (27.22~39.95)	44.58 (38.14~51.03)	42.42 (35.12~49.71)		<0.001 *** (0.771)		
FMA shoulder/elbow	Clinic	19.58 (16.72~22.44)	19.33 (15.90~22.76)	19.58 (16.47~22.70)	23.50 (19.38~27.62)	22.08 (19.30~24.87)		<0.001 *** (0.702)	0.060 (0.152)	0.100 (0.118)
	Lab	21.25 (17.59~24.91)	21.75 (18.01~25.49)	21.58 (17.68~25.49)	28.50 (24.40~32.60)	27.17 (22.65~31.68)	<0.001 *** (0.527)			
FMA wrist/hand	Clinic	9.50 (6.77~12.23)	9.42 (6.99~11.85)	8.83 (6.22~11.44)	11.75 (9.56~13.94)	9.58 (6.72~12.44)		0.005 ** (0.442)	0.047 # (0.167)	0.016 # (0.237)
	Lab	12.00 (9.00~15.00)	11.83 (8.68~14.99)	12.08 (9.01~15.15)	16.08 (13.02~19.14)	15.25 (11.91~18.59)	<0.001 *** (0.471)			
ARAT	Clinic	16.17 (7.80~24.53)	15.42 (7.05~23.79)	15.50 (7.59~23.41)	20.42 (12.46~28.37)	16.33 (9.16~23.51)		0.001 *** (0.608)	0.118 (0.107)	0.014# (0.246)
	Lab	19.58 (12.32~26.85)	18.92 (11.96~25.87)	19.83 (12.46~27.20)	27.00 (18.88~35.12)	24.25 (16.79~31.71)	<0.001 *** (0.554)			
FIM	Clinic	62.75 (60.25~65.25)	62.75 (60.25~65.25)	62.75 (60.25~65.25)	63.25 (61.10~65.40)	63.50 (61.34~65.66)		0.061 (0.233)	0.284 (0.052)	0.671 (0.008)
	Lab	65.58 (64.45~66.72)	65.58 (64.45~66.72)	65.58 (64.45~66.72)	65.75 (64.60~66.90)	65.75 (64.60~66.90)		0.166 (0.167)		
WMFT score	Clinic	36.92 (28.95~44.89)	36.67 (28.54~44.80)	37.08 (29.27~44.90)	42.92 (35.64~50.19)	40.33 (33.30~47.36)		<0.001 *** (0.780)	0.549 (0.017)	0.352 (0.040)
	Lab	39.33 (30.99~47.68)	38.58 (29.99~47.18)	39.75 (30.90~48.60)	46.08 (37.34~54.83)	43.33 (34.97~51.69)	<0.001 *** (0.543)			
WMFT time	Clinic	66.48 (54.34~78.61)	66.09 (53.22~78.97)	65.32 (50.92~79.71)	61.77 (47.33~76.20)	61.89 (47.07~76.71)		0.338 (0.090)	0.017 # (0.232)	0.496 (0.021)
	Lab	53.63 (40.13~67.14)	54.35 (40.01~68.69)	50.34 (37.15~63.54)	44.80 (33.26~56.34)	48.35 (36.36~60.34)	<0.001 *** (0.293)			
MAS elbow	Clinic	1.70 (1.41~1.99)	1.67 (1.44~1.90)	1.77 (1.54~2.00)	1.37 (1.14~1.59)	1.58 (1.33~1.83)		0.005 ** (0.438)	0.247 (0.060)	0.126 (0.103)

MAS wrist	Lab	2.03 (1.39~2.68)	2.08 (1.45~2.72)	2.08 (1.45~2.72)	1.45 (0.77~2.13)	1.70 (0.98~2.42)	<0.001 *** (0.406)	0.257 (0.058)	0.997 (<0.001)
	Clinic	1.45 (0.95~1.95)	1.35 (0.97~1.73)	1.30 (0.94~1.66)	0.98 (0.63~1.33)	1.02 (0.66~1.37)	0.007 ** (0.419)		
MAS finger	Lab	2.03 (1.33~2.73)	2.12 (1.35~2.89)	2.03 (1.24~2.83)	1.20 (0.49~1.91)	1.50 (0.76~2.24)	<0.001 *** (0.477)	0.134 (0.099)	0.219 (0.068)
	Clinic	1.70 (1.19~2.21)	1.52 (1.04~2.00)	1.60 (1.05~2.15)	1.23 (0.87~1.60)	1.35 (0.97~1.73)	0.014 * (0.354)		
	Lab	2.03 (1.45~2.62)	2.02 (1.38~2.65)	1.98 (1.39~2.58)	1.37 (0.69~2.05)	1.57 (1.01~2.12)	<0.001 *** (0.658)		

The superscript "*" and "#" denote the significant intragroup and intergroup difference, respectively. One superscript indicates $p \leq 0.05$, two superscripts indicate $p \leq 0.01$, and three superscripts indicate $p \leq 0.001$.

3.4.2 EMG-assessed improvements in muscle coordination

Changes in muscle activation and coordination were analyzed using multi-channel EMG signals. As illustrated in Figure 3.5, the clinic group demonstrated a significant post-training reduction ($p \leq 0.05$) in the EMG activation level of the ECU-ED muscle. In contrast, the lab group showed significant reductions ($p \leq 0.05$) in the activation levels of both the APB and FCR-FD muscles. The CI, which measures muscle pair independence, also showed distinct changes between the two groups. The lab group achieved significant decreases ($p \leq 0.05$) in the CI values for seven muscle pairs, including APB/BIC, BIC/TRI, ECU-ED/FCR-FD, ECU-ED/BIC, FCR-FD/APB, FCR-FD/BIC, and FCR-FD/TRI. Meanwhile, the clinic group only showed a significant reduction ($p \leq 0.05$) in CI for the FCR-FD/APB muscle pair. Furthermore, the lab

group's post-training CI values were significantly lower ($p \leq 0.05$) than those of the clinic group for five of these pairs: ECU-ED/FCR-FD, ECU-ED/BIC, FCR-FD/APB, FCR-FD/BIC, and APB/BIC. The full EMG results are provided in Table 3.4.

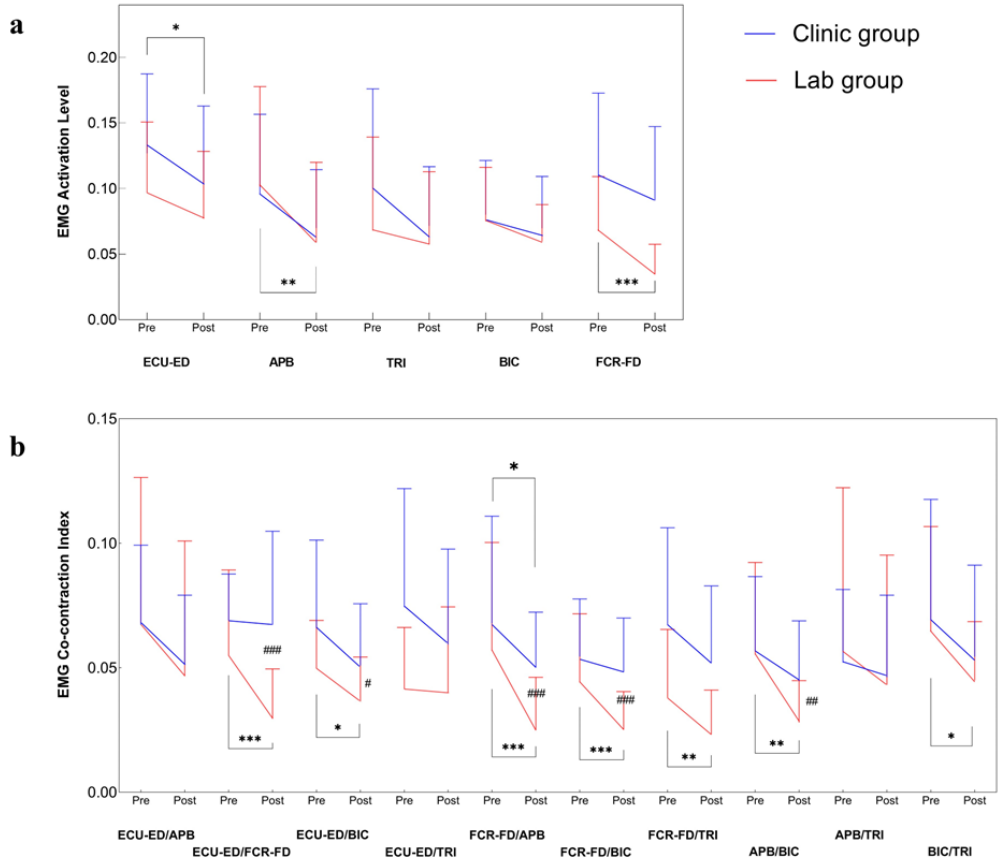

Figure 3.5 Improved muscular coordination for both groups before and after training. (**a**) Normalized EMG activation levels and (**b**) normalized CI. Data are shown as mean ± SD. The symbols "*" and "#" denote significant intragroup and intergroup differences, respectively. One symbol indicates $p \leq 0.05$, two symbols indicate $p \leq 0.01$, and three symbols indicate $p \leq 0.001$.

Table 3.4 Normalized EMG activation level and normalized CI for both groups at pre- and post-training assessments.

EMG Parameters	Group	Pre	Post	Paired t-Test	Wilcoxon Signed Rank Test	Independent t-Test	Mann–Whitney U Test
		Mean Value (95% Confidence Interval)		*p* (Cohen's d)	*p* (r)	*p* (Cohen's d)	*p* (r)
Normalized EMG activation level							
ECU-ED	Clinic	0.13 (0.10~0.15)	0.10 (0.08~0.13)		0.032 * (0.31)		0.143(0.21)
	Lab	0.10 (0.07~0.12)	0.08 (0.06~0.10)	0.228(0.37)			
APB	Clinic	0.10 (0.07~0.12)	0.07 (0.05~0.09)		0.123(0.22)		0.108(0.23)
	Lab	0.10 (0.07~0.13)	0.06 (0.03~0.08)		0.003 ** (0.43)		
TRI	Clinic	0.10 (0.07~0.13)	0.07 (0.05~0.09)		0.209(0.18)	/	
	Lab	0.07 (0.04~0.10)	0.06 (0.03~0.08)	0.525(0.16)			
BIC	Clinic	0.08 (0.06~0.10)	0.07 (0.05~0.09)	0.306(0.25)		0.314(0.29)	
	Lab	0.08 (0.06~0.09)	0.06 (0.05~0.07)	0.086(0.44)			
FCR-FD	Clinic	0.11 (0.08~0.14)	0.09 (0.07~0.11)		0.123(0.22)	/	
	Lab	0.07 (0.05~0.09)	0.03 (0.02~0.04)	<0.001 *** (0.99)			
Normalized co-contraction index							
ECU-ED/APB	Clinic	0.07 (0.05~0.08)	0.05 (0.04~0.06)		0.067(0.26)		0.083(0.25)
	Lab	0.07 (0.04~0.09)	0.05 (0.02~0.07)	0.169(0.37)			
ECU-ED/FCR-FD	Clinic	0.07 (0.06~0.08)	0.07 (0.05~0.08)		0.376(0.13)		<0.001 ### (0.55)
	Lab	0.05 (0.04~0.07)	0.03 (0.02~0.04)	0.001 *** (0.90)			
ECU-ED/BIC	Clinic	0.07 (0.05~0.08)	0.05 (0.04~0.06)		0.059(0.27)	0.026 # (0.67)	
	Lab	0.05 (0.04~0.06)	0.04 (0.03~0.04)	0.019 * (0.71)			
ECU-ED/TRI	Clinic	0.07 (0.05~0.09)	0.06 (0.04~0.08)		0.290(0.15)	/	
	Lab	0.04 (0.03~0.05)	0.04 (0.03~0.05)	0.843(0.04)			
FCR-FD/APB	Clinic	0.07 (0.05~0.09)	0.05 (0.04~0.06)	0.050 * (0.52)			<0.001 ### (0.53)
	Lab	0.06 (0.04~0.08)	0.03 (0.02~0.03)		0.001 *** (0.47)		
FCR-FD/BIC	Clinic	0.05 (0.04~0.06)	0.05 (0.04~0.06)	0.248(0.28)		<0.001 ### (1.23)	
	Lab	0.04 (0.03~0.06)	0.03 (0.02~0.03)	0.001 *** (0.85)			
FCR-FD/TRI	Clinic	0.07 (0.05~0.08)	0.05 (0.04~0.07)		0.179(0.19)	/	
	Lab	0.04 (0.03~0.05)	0.02 (0.02~0.03)	0.006 ** (0.64)			
APB/BIC	Clinic	0.06 (0.04~0.07)	0.04 (0.03~0.05)	0.106(0.44)		0.008 ## (0.80)	
	Lab	0.06 (0.04~0.07)	0.03 (0.02~0.04)	0.003 ** (0.95)			
APB/TRI	Clinic	0.05 (0.04~0.06)	0.05 (0.03~0.06)		0.440(0.11)		0.099(0.24)
	Lab	0.06	0.04	0.351(0.23)			

		(0.03~0.08)	(0.02~0.07)			
BIC/TRI	Clinic	0.07 (0.05~0.09)	0.05 (0.04~0.07)		0.219(0.18)	0.536(0.09)
	Lab	0.06 (0.05~0.08)	0.04 (0.03~0.05)	0.031 * (0.58)		

The superscript "*" and "#" denote the significant intragroup and intergroup difference, respectively. One superscript indicates $p \leq 0.05$, two superscripts indicate $p \leq 0.01$, and three superscripts indicate $p \leq 0.001$.

3.4.3 Changes in kinematic performance

3D kinematic measurements were taken to assess changes in motion smoothness and compensatory movements (Figure 3.6). A significant reduction in the NMUs was demonstrated in the two groups following the training ($p \leq 0.05$), indicating an improvement in motion smoothness. Regarding MTD, the lab group showed a significant decrease post-training ($p \leq 0.05$), while the clinic group presented a non-significant increase ($p > 0.05$). This resulted in a significant difference in MTD between the two groups post-training ($p \leq 0.05$). The lab group's mean decreases in MTD (mean = −20.0958; 95% CI: −38.7219 to −1.4698) was significantly greater than the clinic group's mean increase (mean = 10.9202; 95% CI: −5.8523 to 27.6926), with a p-value of 0.014. No significant difference was found in the NMU changes between the two groups ($p = 0.742$). Full kinematic results are detailed in Table 3.5.

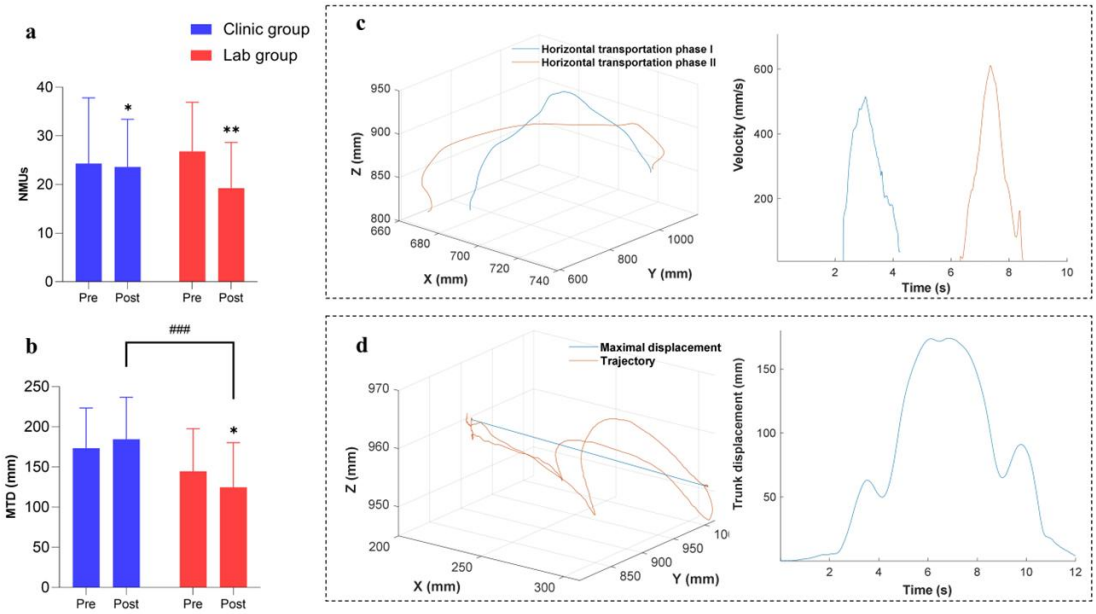

Figure 3.6 Improved kinematic performance for both groups before and after the training. (**a**) NMUs and (**b**) MTD. Data are shown as means ± SDs. The symbols "*" and "#" denote significant intragroup and intergroup differences, respectively. One symbol indicates $p \leq 0.05$, two symbols indicate $p \leq 0.01$, and three symbols indicate $p \leq 0.001$. (**c**) Example of hand-marker trajectory and velocity profile in a trial during the horizontal task transport phase. (**d**) Example of thorax-marker trajectory and displacement profile in a trial during the horizontal task.

Table 3.5 NMUs and MTD for both groups at pre- and post-assessments.

Kinematic Parameters	Group	Pre	Post	Paired t-Test	Wilcoxon Signed Rank Test	Independent t-Test	Mann–Whitney U Test
		Mean Value (95% Confidence Interval)		*p* (Cohen's d)	*p* (r)	*p* (Cohen's d)	*p* (r)
NMUs	Clinic	30.02 (24.33~35.71)	23.63 (19.50~27.77)		0.040 * (0.30)		0.054(0.28)
	Lab	26.83 (22.57~31.09)	19.25 (15.28~23.22)	0.003 ** (0.78)			
MTD	Clinic	173.53 (152.42~194.63)	184.45 (162.33~206.56)	0.191(0.21)		<0.001 ### (1.11)	
	Lab	144.79 (122.52~167.06)	124.69 (101.22~148.16)	0.036 * (0.37)			

The superscript "*" and "#" denote the significant intragroup and intergroup difference, respectively. One superscript indicates $p \leq 0.05$, two superscripts indicate $p \leq 0.01$, and three superscripts indicate $p \leq 0.001$.

3.4.4 Tele-monitoring of training performance

Table 3.6 shows the data from remote monitoring. A similar number of participants received caregiver assistance with device operation in both groups, seven in the clinic group and six in the lab group. The average weekly training frequency was slightly higher in the lab group (3.75 ± 0.72 sessions/week) compared to the clinic group (3.33 ± 0.47 sessions/week). However, the average duration per session was significantly longer in the clinic group (91.30 ± 8.50 minutes/session) than in the lab group (62.80 ± 1.93 minutes/session). Consequently, the clinic group completed a higher average number of movement cycles per session (184.23 ± 30.46 cycles/session) compared to the lab group (115.20 ± 9.50 cycles/session).

Table 3.6 Logistic data of participants for both groups.

Parameters	Frequency (session/week)	Duration (min/session)	Complete movement cycles (cycle/session)
Clinic Group (n = 12)	3.33 ± 0.47	91.30 ± 8.50	184.23 ± 30.46
Lab Group (n = 12)	3.75 ± 0.72	62.80 ± 1.93	115.20 ± 9.50

Values are presented as mean ± SD for each parameter.

3.4.5 Questionnaire outcomes

Questionnaire responses were collected from 11 participants in the clinic group and 10 participants in the laboratory-based group (Figure 3.7). All dimensions of the USE questionnaire showed a mean score above the neutral point (50%), and the lab group consistently reported higher mean scores than the clinic group. Similarly, the lab cohort demonstrated higher mean scores across most subscales of the IMI. A statistically significant between-group difference was identified in the value/usefulness subscale of IMI ($p \leq 0.05$), suggesting that participants in the lab group perceived the training program as more valuable compared to those in the clinic group. Table 3.7 provides a summary of the USE and IMI scores for each group.

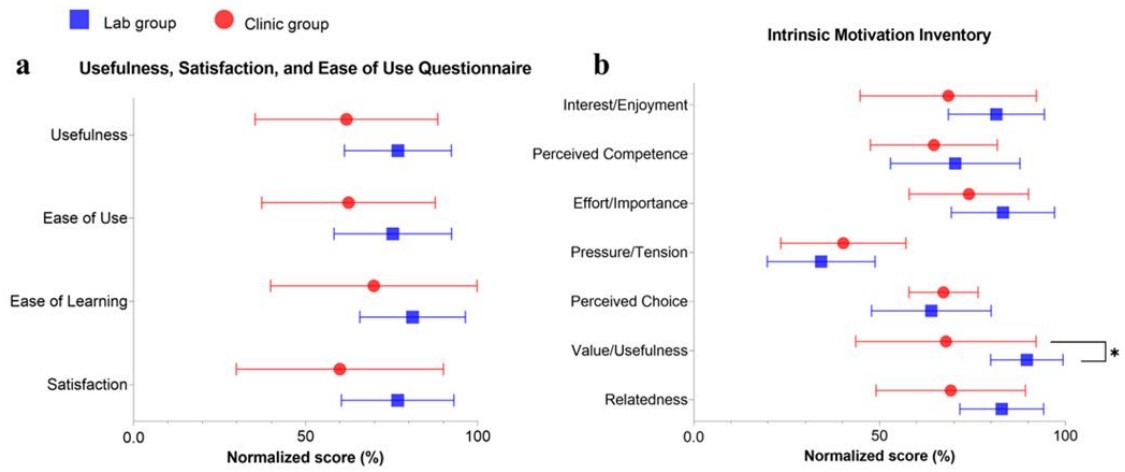

Figure 3.7 Normalized results of (**a**) USE and (**b**) IMI for both groups. Data are shown as means (mean%) ± SD (SD%). The symbol "*" denotes significant intergroup differences, with one symbol indicating $p \leq 0.05$.

Table 3.7 USE and IMI scores for both groups.

	Clinic Group		Lab Group		Independent t-Test	
	Mean ± SD	**Mean% ± SD%**	**Mean ± SD**	**Mean% ± SD%**	***p***	**Cohen's d**
USE						
Usefulness	34.64 ± 14.86	61.85% ± 26.54%	43.00 ± 8.71	76.79% ± 15.55%	0.137	0.68
Ease of Use	48.09 ± 19.42	62.46% ± 25.22%	58.00 ± 13.16	75.32% ± 17.09%	0.192	0.59
Ease of Learning	19.55 ± 8.64	69.81% ± 30.86%	22.70 ± 4.30	81.07% ± 15.34%	0.300	0.46
Satisfaction	29.36 ± 14.75	59.93% ± 30.10%	37.60 ± 8.00	76.73% ± 16.33%	0.127	0.68
IMI						
Interest/Enjoyment	4.80 ± 1.66	68.51% ± 23.73%	5.70 ± 0.90	81.43% ± 12.91%	0.143	0.67
Perceived Competence	4.52 ± 1.20	64.61% ± 17.09%	4.93 ± 1.22	70.36% ± 17.42%	0.455	0.33
Effort/Importance	5.18 ± 1.12	74.03% ± 16.06%	5.83 ± 0.97	83.21% ± 13.89%	0.179	0.61
Pressure/Tension	2.82 ± 1.18	40.26% ± 16.83%	2.40 ± 1.02	34.29% ± 14.50%	0.397	0.38
Perceived Choice	4.70 ± 0.65	67.21% ± 9.29%	4.48 ± 1.13	63.93% ± 16.10%	0.581	0.25
Value/Usefulness	4.75 ± 1.70	67.86% ± 24.28%	6.28 ± 0.68	89.64% ± 9.74%	0.016 *	1.16
Relatedness	4.84 ± 1.41	69.16% ± 20.09%	5.80 ± 0.79	82.86% ± 11.27%	0.073	0.83

The superscript "*" denotes the significant intergroup difference, with one superscript indicating $p \leq 0.05$. For IMI, 7-point Likert scale: 1 = "not at all true" to 7 = "very true". For USE, 7-point Likert scale: 1 = "strongly disagree" to 7 = "strongly agree".

3.5 Discussion

This study provides evidence that the WH-ENMS telerehabilitation program can be successfully integrated into a routine clinical service. Our results, derived from clinical scores, EMG parameters, and kinematic data, consistently show significant motor

recovery in the paretic upper limb following the training.

3.5.1 Training outcome

The telerehabilitation program proved effective in improving voluntary motor function across the entire paretic limb, as evidenced by significant gains in the FMA-UE, its subscales (FMA shoulder/elbow and FMA wrist/hand), and the ARAT for both groups (Figure 3.4). These findings are consistent with other research on RAT for distal joints, which also reported concurrent improvements in both proximal and distal upper limb function [127, 128]. This may be attributed to several factors: (1) the training tasks required coordinated movements of both proximal and distal joints [35]; (2) proximal joints often compensate for distal joint deficits during training [128]; and (3) the interplay between proximal and distal joint movements engages related muscle groups [129]. Despite these general improvements, the lab group demonstrated superior outcomes in the voluntary motor function of the entire paretic limb, where their improvements were more significant and sustained for three months. In contrast, the clinic group showed less improvement in distal joint function, and these gains were not maintained at the 3MFU. These differences highlight that the specific implementation scheme of the clinical translation significantly impacts long-term recovery, a point we will discuss further.

The WMFT, which assesses functional ADLs [121], showed that both groups improved their ability to perform daily tasks post-training, with these gains maintained at 3MFU

(Figure 3.4). The lab group, however, also saw a significant improvement in task completion speed, as indicated by a decrease in WMFT time (Figure 3.4), suggesting more efficient movement coordination. No significant changes were observed in FIM scores following the training (Figure 3.4), likely because this measure is broadly used to assess overall independence in ADLs [120]. The lack of significant change in FIM scores for either group suggests that while the WH-ENMS-assisted telerehabilitation improved specific upper limb functions, it did not lead to a broad improvement in overall ADL independence for these chronic stroke survivors.

Spasticity, measured by the MAS, decreased significantly in the elbow, wrist, and finger joints for the two groups following training (Figure 3.4). This reduction in spasticity can improve muscle coordination and joint stability [130], was maintained at 3MFU in the distal joints in the two groups (Figure 3.4). However, the clinic group showed a greater tendency for spasticity to rebound at the 3MFU compared to the lab group (Figure 3.4), suggesting that the lab group's training approach was more effective at long-term spasticity management.

Reduced EMG activation levels in the ECU-ED muscle, which reflect improved neural control of a specific muscle [81], were observed in the clinic group (Figure 3.5a). These decreases corresponded with lower MAS scores, suggesting enhanced muscular control. Similarly, the lab group's significant reduction in EMG activation of the APB and FCR-FD muscles indicated released spasticity in the distal joints, linking their MAS score

improvements to better muscle control (Figure 3.4 and Figure 3.5a). The EMG CI, which quantifies muscular coordination, showed significant post-training reductions, indicating improved independence between muscle pairs. The reduction in CI values observed in the FCR-FD/APB muscle pair across both groups suggests a more segmented or independent neural control of the fingers and thumb during hand grasping and releasing tasks (Figure 3.5b). This finding is consistent with the recognized role of the APB as a primary muscle enabling thumb opposition [131]. A reduction in elbow compensation during finger movements was observed in the lab group, as reflected by decreased CI values for finger muscles relative to BIC (Figure 3.5b). Abnormal co-contraction in the paretic limb is metabolically inefficient and impairs movement accuracy and efficiency post-stroke [132]. The lab group demonstrated significantly greater reductions in CI values for multiple key muscle pairs compared to the clinic group (Figure 3.5b). These reductions may contribute to their improved WMFT time and the sustained improvements in FMA wrist/hand and ARAT scores observed at 3MFU (Figure 3.4). This indicates that the lab group's training fostered more efficient, independent muscle activity.

Both groups showed a significant decrease in the NMUs following training, indicating smoother movements and improved fine motor control (Figure 3.6a) [124, 133]. Compared with the clinic group, the greater reduction in NMUs observed in the lab group following training may be associated with enhanced muscular coordination, as

reflected in the CI pattern derived from EMG signals (Figure 3.5b and Figure 3.6a). MTD, a measure of compensatory movement, reduced significantly for the lab group but demonstrated a non-significant increase in the clinic group, highlighting a key difference in training outcomes (Figure 3.6b). The superior performance of the lab group in minimizing compensatory movements is likely a result of improved muscular coordination and reduced spasticity. Although reductions in spasticity and lower EMG CI values were also observed in the paretic upper limb of the clinical group, their inferior performance in MTD may be attributed to differences in clinical support protocols, such as variations in how robotic assistance was provided during task completion. These methodological differences further contributed to the disparities in functional improvements between groups, as assessed through both clinical outcome measures and EMG parameters.

Despite the lab group having participants who were more chronic post-stroke, they achieved better overall motor improvements. This suggests that the time since stroke onset was not the primary factor determining the rehabilitative outcome in this study. Instead, the specific training approach, particularly the handling of compensatory strategies, appeared to be the key determinant.

3.5.2 Supporting schemes during clinical translation

The disparity in outcomes between the two groups can be directly linked to the differences in their respective training schemes. In standard clinical practice, therapists

often allow compensatory strategies to help patients achieve independence in ADLs quickly, especially given limited resources for hospital stays [134, 135]. However, this approach can hinder long-term recovery by promoting learned non-use of distal muscles [108, 136]. In the clinic group, operators encouraged task completion even with compensatory movements. In the lab group, assistance was provided solely as needed to minimize compensatory movements and promote effective motor recovery. This approach in the clinic group, while aligned with some principles of task-oriented rehabilitation, resulted in participants relying on trunk and unaffected limb movements, which likely limited VMEs from the affected limb. This was reflected in their smaller reduction in EMG CI values post-training. Furthermore, once established, motor patterns, including compensatory strategies, tend to generalize to participants' ADLs [137]. The long-term consequences of this approach were evident in the compromised maintenance of motor gains, as seen by the rebound in FMA wrist/hand and ARAT scores at 3MFU (Figure 3.4). The extended session duration implemented in the clinic group (90 minutes per session) failed to counteract this decline, underscoring that the efficacy of motor relearning depends not merely on training intensity but fundamentally on the quality and structure of the therapeutic regimen.

3.5.3 The quality of patient-operator interactions

Training results were strongly influenced by how patients and operators engaged with each other [138]. Many people with neurological impairments struggle to adapt when

rehabilitation involves robotics or remote systems, often showing reluctance or skepticism toward these unfamiliar approaches. Their openness to innovation and trust in new methods is typically lower than that of individuals without such impairments [139]. Participants in the lab group were provided with continuous, individualized supervision throughout the entire 60-minute session. This high level of engagement, featuring real-time feedback and personalized guidance, facilitated patient acclimation to the technology and reduced initial apprehensions toward its use. This built confidence and enhanced their engagement, ultimately leading to better outcomes. In the clinic group, patient-operator interactions were limited to an average of 30 minutes per mandatory session due to the constraints of a public healthcare system with limited resources [24]. Beyond onsite interactions, a key challenge in the self-help, home-based sessions was the lack of timely responses to patient inquiries. Because public clinical services were often overloaded, therapists in the clinic group could not always provide prompt feedback. This absence of immediate support during ongoing home sessions may have undermined engagement and motivation. Indeed, participants in the clinic group reported feeling less supported and motivated to pursue motor recovery, as reflected by their lower IMI scores compared with the lab group (Figure 3.7b). Nevertheless, according to the USE results (Figure 3.7a), both groups expressed generally positive experiences with the usability of the WH-ENMS device, achieving normalized scores above 50% across all items. No group difference was found in USE outcomes, even though the clinic group experienced fewer patient-operator interactions.

By contrast, IMI results highlighted that reduced professional support and feedback in the clinic group diminished participants' confidence and motivation, ultimately producing a significant group difference in the perceived value of the training program. These findings suggest that providing continuous, timely feedback—whether delivered onsite or remotely—can strengthen patient engagement and improve rehabilitation outcomes.

Enhancing patient-operator interaction can be achieved by strengthening the operator's supervisory efficiency, enabling them to effectively transfer essential skills to patients or caregivers in preparation for semi-independent self-help sessions. In this study, the lab group's operator had prior experience overseeing telerehabilitation with the WH-ENMS, whereas the clinical group operator lacked such a background in poststroke telerehabilitation [35]. This difference was reflected in participants' usability feedback (Figure 3.7a). In the clinic group, three individuals rated the WH-ENMS as difficult to master, giving less than 50% across all USE dimensions. These findings suggest that structured training sessions focused on self-help skill acquisition could improve acceptance and usability of the device. Operator competence may further be strengthened through dedicated technical training, consultation with experienced rehabilitation researchers, such as methods to reduce compensatory movements, and the gradual accumulation of practical experience through wider service delivery.

While the present study demonstrated statistically significant intra- and inter-group

differences, larger multi-center trials with expanded samples are warranted to establish the clinical value of ENMS-assisted telerehabilitation after stroke. Future studies should incorporate monitoring of training-induced mental fatigue and movement quality to obtain a more comprehensive understanding of the rehabilitation process.

3.6 Periodic summary

Chapter 3 explored the feasibility of translating a robot-assisted telerehabilitation program for post-stroke upper limb recovery into a public rehabilitation center and compared the effectiveness with lab-based telerehabilitation via a non-randomized controlled trial. The program used the WH-ENMS, a lightweight EMG-triggered robot combining pneumatic actuation and NMES. The study demonstrated that the robot-assisted telerehabilitation program could be successfully translated into a routine clinical setting, and participants in both groups achieved significant motor recovery in the paretic upper limb. However, the lab group achieved greater and more sustained improvements in distal hand function. This study demonstrated that the implementation approach of rehabilitation training substantially influences its effectiveness, which encompasses the type of compensatory support strategies, the quality of patient-operator interaction, and the perceived usability for independent home-based practice.

CHAPTER 4

LONG-TERM EFFECTS OF EXONEUROMUSCULOSKELETON-ASSISTED WRIST-HAND TELEREHABILITATION AFTER STROKE

4.1 Introduction

Stroke is a leading cause of adult disability globally, with up to 85% of survivors experiencing lasting upper limb impairments. The recovery of distal joints, such as the wrist and hand, is particularly challenging, as it often lags behind that of proximal joints [140, 141]. Intensive, repetitive practice is crucial for motor restoration, even in the chronic phase [142]. However, a shortage of professional staff and a focus on subacute care mean that many patients discharged home do not have access to the necessary long-term rehabilitation services [143], especially for the wrist and hand. Rehabilitation robots have emerged as a promising solution to this problem, offering a way to deliver high-intensity training to complement conventional therapy [144]. Studies have shown that robot-assisted interventions can be as effective as, or even superior to, traditional treatments in improving upper limb motor function [145].

Home-based telerehabilitation with robotic assistance has the potential to augment public healthcare services by allowing patients to train in their own homes, reducing the burden of travel and healthcare costs. In contrast to traditional center-based therapy, conducting RAT within the home environment may promote more effective integration

of practice into daily routines over the long term, while also reducing travel requirements and overall healthcare burden [146]. However, successfully translating these programs into real-world clinical practice remains a significant challenge. The complexities of managing and preparing for telerehabilitation can influence training outcomes [67]. Furthermore, a critical gap in current research is the lack of long-term follow-up data. Most studies focus on immediate post-intervention outcomes, with little attention paid to whether these gains are sustained over time [147]. Long-term follow-up studies are often hindered by high dropout rates, particularly among stroke survivors with unstable neurological conditions or those who relocate, which can introduce biases into the results. The long-term effects of robot-assisted interventions, especially for chronic stroke, are clinically vital for assessing the stability and generalization of therapeutic gains. Previous research has produced mixed results on this topic. One study found that initial improvements in FMA-UE and FIM scores from robotic therapy were not sustained at a 6-month follow-up (6MFU) [148]. This highlights the uncertainty surrounding the long-term persistence of such gains. Additionally, these studies have predominantly relied on subjective clinical assessments, which lack the objectivity and precision of quantitative methods. A need exists for more thorough investigations using objective measures like EMG and kinematic assessments to better understand the underlying muscular and kinematic changes.

In our prior work, we developed a mobile ENMS that combines NMES with robotic

assistance for upper limb rehabilitation [32]. We successfully transitioned a self-help telerehabilitation program [67], which utilized the WH-ENMS, from a laboratory setting to a local public rehabilitation center. This initial study involved 12 participants with chronic stroke and demonstrated significant short-term motor improvements with no adverse events [67].

4.2 Study aims

Building on our work in Chapter 3, we extended the telerehabilitation program by recruiting 22 chronic stroke survivors in the clinical service. The primary purpose of this study was to investigate the long-term effects of the WH-ENMS-assisted telerehabilitation program, with a focus on outcomes up to six months post-training. Our research provided an analysis of these long-term benefits by integrating behavior changes, muscular improvements, and kinematic performance.

4.3 Methods

This study used a single-group pre-post design, with follow-up assessments at three and six months (3MFU and 6MFU). The program involved 20 home-based sessions of wrist-hand training for chronic stroke survivors with upper limb impairments. All sessions were conducted with WH-ENMS. Ethical approval was granted by the Human Participants Ethics Sub-Committee at The Hong Kong Polytechnic University and the Research Ethics Committee at Kowloon Central and Kowloon East.

4.3.1 EMG-driven WH-ENMS

The WH-ENMS is a hybrid system combining pneumatic actuation with NMES, regulated by residual EMG signals from the user's affected upper extremity. The system is designed to assist stroke survivors with phased, repetitive, and coordinated wrist and hand motions, i.e., wrist extension with the hand open and wrist flexion with the hand closed [32]. The WH-ENMS system consists of several key components: a glove with embedded pneumatic fingers and a 3D-printed exoskeletal connector; two channels of EMG-NMES; a pump and control box powered by a rechargeable 12-V battery; and a corresponding smartphone App that wirelessly connects to the control box via Bluetooth [32]. The control mechanism of the system relies on EMG-triggered technology. The ECU and ED muscles were combined into a single muscle union (i.e., ECU-ED), as were the FCR and FD combined into another muscle union (i.e., FCR-FD), due to their close anatomical locations. These two muscle unions function as neuromuscular triggers to initiate mechanical and NMES assistance during each movement phase. Two pairs of reusable surface electrodes, placed on the motor points of these muscle bellies, were used by the two EMG-NMES channels for both EMG signal detection and NMES delivery [35]. During the "wrist extension with the hand open" phase, the pneumatic fingers inflate to provide assistive torque once the ECU-ED's EMG activation reaches a preset threshold. Conversely, for the "wrist flexion with the hand closed" phase, the pneumatic fingers passively deflate when the FCR-FD's

EMG activation level meets its threshold, which allows for voluntary finger flexion. NMES is delivered to assist both wrist extension (via ECU-ED) and wrist flexion (via FCR-FD). A reference electrode was placed on the olecranon to minimize common-mode electrical noise.

4.3.2 Participants

Building on our prior work at the CRSSC of the Hospital Authority in Hong Kong [67], we continued to recruit participants from outpatients at this facility from April 2020 to March 2023. Inclusion criteria for participants were as follows: (1) single, unilateral brain lesion from a stroke that occurred more than 12 months prior; (2) MAS score below 3 at the elbow, wrist, and finger [114]; (3) FMA-UE score greater than 15 [115]; (4) MMSE score exceeding 21 [149]; (5) detectible voluntary EMG signals in the driving muscles (ECU-ED, FCR-FD) on the affected side, defined as three times the SD over the baseline; (6) FIM score of at least 51; (7) the ability to meet minimal home requirements for training, including a stable, armless chair, a table with a minimum surface area of 60 × 40 cm^2, and access to a 3G or higher mobile network. Participants were excluded if they: (1) had a history of epilepsy; (2) had a cardiac pacemaker or other implants; (3) had open wounds or skin lesions in the electrode areas; (4) had acute inflammation; (5) suffered from shoulder pain or central post-stroke pain; (6) had other neurological impairments; or (7) were concurrently receiving other upper limb treatments.

4.3.3 Training protocol

The telerehabilitation program was composed of 20 WH-ENMS-assisted training sessions conducted over seven consecutive weeks (Figure 4.1). The program's intensity was 3-5 sessions per week, with a maximum of one session per day, and each session lasted between 60 and 90 minutes. The program began with three mandatory courses in the clinic, followed by the remaining self-help sessions at home. The experiment operators were a registered OT and an OTA employed by the CRSSC. They provided on-site professional supervision during the mandatory courses and remote supervision for the home-based sessions by monitoring automated feedback from the WH-ENMS (e.g., session start/end times and task repetitions).

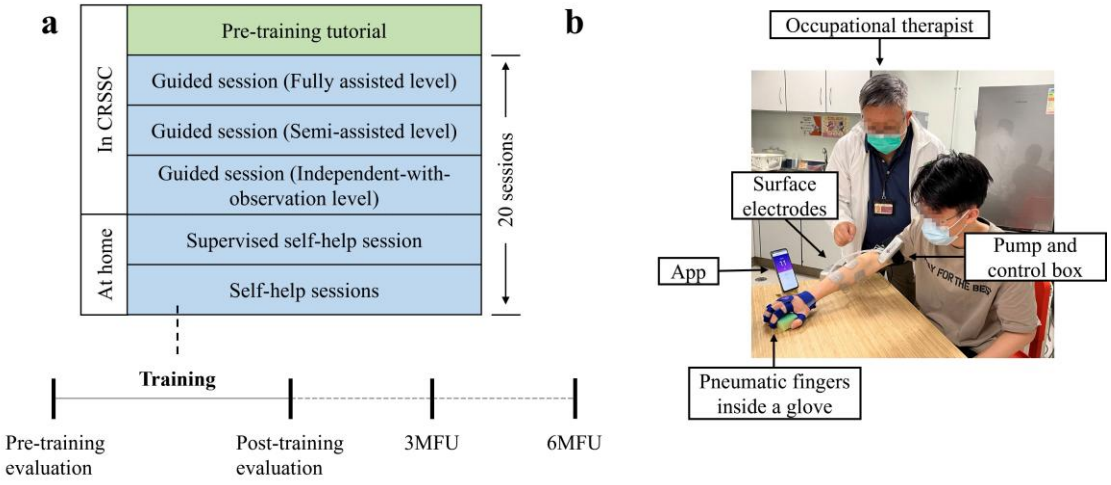

Figure 4.1 Telerehabilitation program assisted by WH-ENMS. (**a**) Timeline of the 20-session program. (**b**) The first self-help home-based session supervised by an OT.

The mandatory courses began with a pre-training tutorial where participants and their

caregivers were instructed on how to don/doff the system, operate it, and follow the training protocols [35]. The experimental operator set all training parameters, including EMG threshold, NMES, and mechanical assistance levels, which remained constant throughout the 20 sessions. A smartphone was loaned to any participant who did not own one. Following the tutorial, participants completed three guided training sessions. During each session, participants sat at a table with their shoulders 30-40 cm above the surface. A smartphone displaying the App, which provided visual cues, was placed 30-60 cm in front of them. The repetitive limb tasks consisted of a horizontal task, a vertical task, and an optional forward task [67]. The horizontal task involved gripping a sponge (8.5×5.5 cm^2) and moving it 50 cm laterally. The vertical task required moving the sponge from under an 18-cm-high shelf to its top. The optional forward task entailed moving the sponge 30 cm forward. Each task was performed for 30 minutes, with a 10-minute rest between tasks to prevent muscle fatigue. On-site feedback from the operators was provided during the guided sessions to support the participants' transition to independent home training. Once an operator deemed a participant competent, they proceeded with the remaining sessions at home. For the first self-help session, an operator visited the participant's home to deliver the equipment, inspect the safety of the environment, and observe a full session to ensure proper execution. As part of the CRSSC's routine management, each participant paid a fee of HKD 375 for the mandatory courses. A detailed description of the experimental protocol has been reported in our previous study [67].

Remote monitoring was a key component of the program. Training data, including training frequency, session duration, and the number of completed movement cycles, were automatically logged by the App and uploaded to a university server. Operators remotely monitored this data and contacted participants by phone or message to schedule make-up sessions if they missed. A backup system was stored at the CRSSC, and any malfunctioning equipment was replaced within one working day to avoid disrupting the protocol. Operators also contacted participants weekly to discuss their experiences. A more detailed description of this experimental protocol has been previously published [67].

4.3.4 Evaluation measures

Participants were evaluated at four time points: pre-training, post-training, and at 3MFU and 6MFU. To establish a reliable baseline, clinical assessments were conducted three times within two weeks, with a minimum two-day interval between them. The mean of these three evaluations was used for all statistical analyses. Objective EMG and kinematic evaluations were also conducted at all four time points. The FMA-UE score was designated as the primary outcome, while all other clinical scores and objective parameters were considered secondary outcomes.

4.3.4.1 Clinical assessments

All clinical evaluations were performed by a blinded assessor who was unaware of the study protocol. The following standardized measures were used: (1) FMA-UE [119]: a

reliable, widely used 66-point scale (42 points for the shoulder and elbow, 24 for the wrist and hand) for detecting motor function improvements. (2) MAS [64]: a common scale used to assess spasticity in the elbow, wrist, and finger flexors. (3) ARAT [150]: evaluates both proximal and distal arm motor function. (4) WMFT [151]: assesses upper limb motor ability through 17 tasks, recording both a score and the time to complete each task. (5) FIM [152]: a general scale that assesses the degree of disability in daily living activities.

4.3.4.2 EMG evaluation

To quantitatively assess muscle activation and coordination, EMG signals were collected from the paretic upper limb muscles, including the ECU-ED, APB, TRI, BIC, and FCR-FD. During each EMG session, MVCs were first recorded for each muscle. This was followed by three repetitions of bare-arm horizontal and vertical tasks, performed without the WH-ENMS. A two-minute rest interval was implemented between trials to minimize muscle fatigue. The EMG signals were amplified, band-pass filtered (10–500 Hz), and sampled at 1000 Hz. During offline processing, the data was rectified and low-pass filtered to create an EMG signal envelope. Two key parameters were used for analysis. The first is activation level [153], defined as the average EMG signal envelope for each muscle normalized against its maximum value during MVCs. A lower activation level suggests improved motor control with less effort. The second is the EMG CI [67], which quantifies the overlap in the EMG signal envelopes of

muscle pairs, serving as a measure of muscle independence. A decreased CI value indicates improved muscular coordination.

4.3.4.3 Kinematic evaluation

Vicon motion capture system was used to track the 3D movements of the paretic upper limb, assessing kinematic performance. Participants performed the same bare-arm tests as in the EMG evaluation, with three repetitions per task and a two-minute break between trials. Two parameters [154] were calculated to evaluate kinematic performance: (1) NMUs, which is a count of significant changes in the tangential velocity of the middle finger's metacarpophalangeal joint. A lower NMU count indicates smoother, more coordinated movement. (2) MTD, which measures the maximum distance the trunk moves from its starting position during a task. It serves as a quantitative measure of compensatory trunk movements.

4.3.5 Statistical analysis

All statistical computations were performed with SPSS version 26 (IBM, Chicago, IL, USA). Initially, a Shapiro–Wilk test [82] was conducted on all outcome variables to check for normality of distribution. Results showed that the WMFT scores and MTD were normally distributed across all four measurement time points ($p > 0.05$). For these normally distributed variables, a one-way repeated measures ANOVA with a Bonferroni post hoc test was used to compare data from the pre-training, post-training, 3MFU, and 6MFU assessments. For all other outcomes that did not meet the assumption of

normality, a Friedman test with a Wilcoxon signed-rank post hoc test was employed [155]. The Bonferroni method was applied to correct for multiple comparisons. Statistical significance was defined as $p \leq 0.05$, with specific levels of $p \leq 0.01$ and $p \leq 0.001$ also noted.

4.4 Results

The CONSORT flowchart for this study is shown in Figure 4.2. Out of 31 outpatients initially screened from the CRSSC, 22 were recruited for the study and provided with written informed consent. Two of these participants later withdrew for personal reasons, resulting in a final cohort of 20 individuals who completed the entire telerehabilitation program.

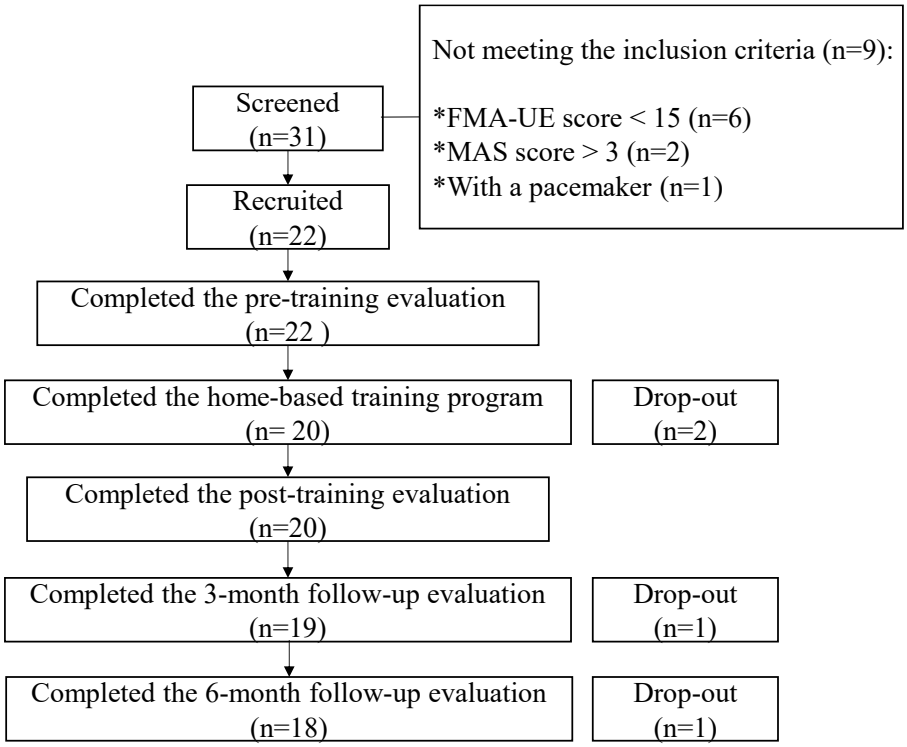

Figure 4.2 The CONSORT flowchart of the study.

Demographic data are shown in Table 4.1. The final cohort consisted of 13 males, with a mean age of 49.75 ± 13.13 years and an average time since stroke of 3.71 ± 3.11 years. Eleven participants had left hemiplegia, while nine had right hemiplegia. Stroke types included six cases of ischemic stroke and 14 cases of hemorrhagic stroke. Logistical data for the program revealed an average training frequency of 3.45 ± 0.67 (mean ± SD) sessions per week, with each session lasting an average of 89.80 ± 11.40 (mean ± SD) minutes. On average, participants completed 173.02 ± 33.62 (mean ± SD) movement cycles per session.

Table 4.1 Demographic data of the participants.

Characteristics	n = 20
Age in years (mean ± SD)	49.75 ± 13.13
Time since stroke in years (mean ± SD)	3.71 ± 3.11
Gender (male/female)	13/7
Hemiplegic side (left/right)	11/9
Stroke type (ischemic/hemorrhagic/unknown)	6/14

The measured clinical scores, assessed at pre-training, post-training, and at the 3MFU and 6MFU, are illustrated in Figure 4.3a. Participants achieved significant increases in FMA-UE ($p \leq 0.05$), its subscales for the shoulder/elbow ($p \leq 0.05$), and the wrist/hand ($p \leq 0.05$) immediately following the training. The improvements in both FMA-UE and FMA shoulder/elbow scores were successfully maintained at both the 3MFU and 6MFU ($p \leq 0.05$). Additionally, a significant increase in the ARAT score was observed after the training ($p \leq 0.05$). There were significant post-training reductions in MAS

scores for the elbow, wrist, and finger joints ($p \leq 0.05$). The decreased spasticity at the wrist was notably retained through the 6MFU ($p \leq 0.05$). Participants demonstrated a significant increase in their WMFT score and a significant decrease in their WMFT time after the training ($p \leq 0.05$). These improvements were sustained at both the 3- and 6MFU ($p \leq 0.05$). The FIM score showed a significant increase only at 6MFU ($p \leq 0.05$), suggesting a delayed but persistent improvement in ADL. A summary of the comparisons for the clinical scores is provided in Table 4.2.

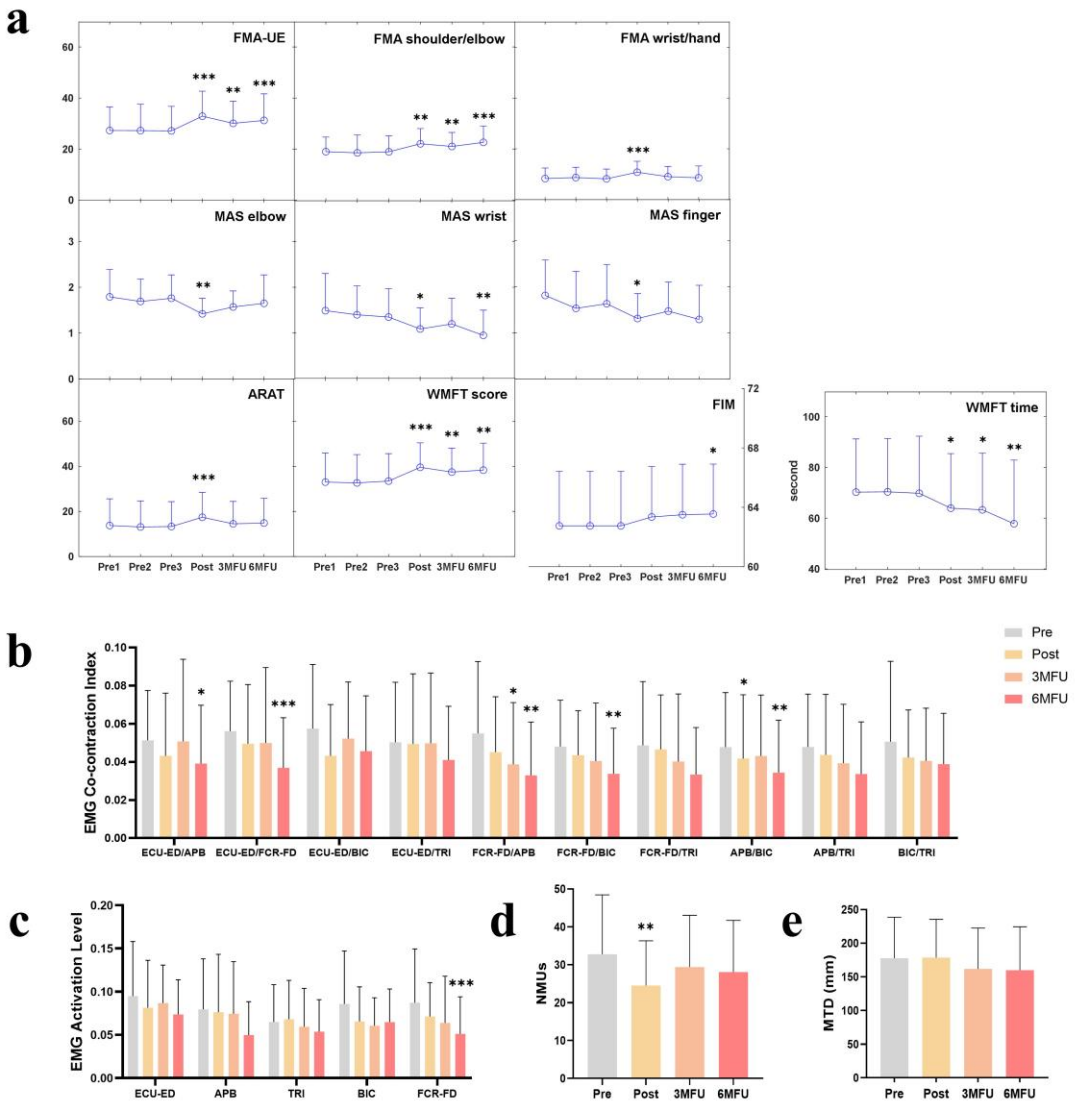

Figure 4.3 Longitudinal assessment results on motor functions at pre-, post-, 3MFU, and 6MFU assessments. (**a**) Clinical scores, (**b**) normalized EMG CI, (**c**) normalized EMG activation levels, (**d**) NMUs, and (**e**) MTD. Data are shown as mean ± SD. The symbols "*" denote significant differences. One symbol indicates $p \leq 0.05$, two symbols indicate $p \leq 0.01$, and three symbols indicate $p \leq 0.001$.

Table 4.2 The clinical scores at the pre-, post-, 3MFU, and 6MFU assessments.

Clinical assessments	Pre1	Pre2	Pre3	Post	3MFU	6MFU	One-way repeated measures ANOVA	Friedman test
	Mean value (95% confidence interval)						p (Partial η^2)	p (Kendall's W)
FMA-UE	27.30(23.00~31.60)	27.25(22.41~32.09)	27.15(22.67~31.63)	32.90(28.31~37.49)	30.10(26.03~34.17)	31.25(26.39~36.11)		0.000*** (0.518)
FMA shoulder/elbow	19.00(16.32~21.68)	18.55(15.30~21.80)	18.95(16.02~21.88)	22.10(19.32~24.88)	21.05(18.49~23.61)	22.65(19.65~25.65)		0.000*** (0.421)
FMA wrist/hand	8.30(6.35~10.25)	8.70(6.81~10.59)	8.20(6.39~10.01)	10.80(8.78~12.82)	9.05(7.17~10.93)	8.60(6.41~10.79)		0.001*** (0.281)
MAS elbow	1.79(1.51~2.07)	1.69(1.46~1.92)	1.76(1.52~2.00)	1.42(1.26~1.58)	1.57(1.41~1.73)	1.65(1.36~1.94)		0.046* (0.133)
MAS wrist	1.49(1.11~1.87)	1.40(1.10~1.70)	1.35(1.06~1.64)	1.09(0.88~1.30)	1.20(0.94~1.46)	0.95(0.69~1.21)		0.001*** (0.286)
MAS finger	1.81(1.45~2.17)	1.53(1.16~1.90)	1.63(1.23~2.03)	1.31(1.06~1.56)	1.47(1.18~1.76)	1.29(0.94~1.64)		0.011* (0.186)
ARAT	13.75(8.22~19.28)	13.10(7.68~18.52)	13.30(8.13~18.47)	17.40(12.24~22.56)	14.50(9.85~19.15)	14.85(9.70~20.00)		0.000*** (0.406)
WMFT score	33.00(26.97~39.03)	32.65(26.77~38.53)	33.45(27.76~39.14)	39.55(34.47~44.63)	37.45(32.50~42.40)	38.30(32.70~43.90)	0.000*** (0.438)	
WMFT time	70.28(60.47~80.10)	70.40(60.56~80.23)	69.82(59.28~80.36)	63.96(53.89~74.03)	63.31(52.85~73.76)	57.83(46.10~69.56)		0.005** (0.213)
FIM	62.75(61.03~64.47)	62.75(61.03~64.47)	62.75(61.03~64.47)	63.35(61.76~64.94)	63.50(61.91~65.09)	63.55(61.98~65.12)		0.001*** (0.281)

The superscript "*" indicates the significant intragroup difference, with 1 superscript denoting $p \leq 0.05$, 2 superscripts denoting $p \leq 0.01$, and 3 superscripts denoting $p \leq 0.001$.

Figures 4.3b-e illustrate the long-term trends for objective metrics, including EMG CI values, EMG activation levels, NMUs, and MTD. For muscular coordination, as measured by EMG CI values, several muscle pairs demonstrated significant long-term reductions. Immediately after training, the CI value for the APB/BIC muscle pair showed a significant decrease. By the 3MFU, the FCR-FD/APB muscle pair also exhibited a significant reduction in its CI value. The most widespread improvements were observed at 6MFU, where significant decreases were identified in the CI values

for five muscle pairs: ECU-ED/APB, ECU-ED/FCR-FD, FCR-FD/APB, FCR-FD/BIC, and APB/BIC (all $p \leq 0.05$). This indicates a progressive improvement in the independence of these muscles over time. In terms of EMG activation levels, a single, but notable, change was a significant decrease in the activation of the FCR-FD muscle at 6MFU ($p \leq 0.05$). This suggests a long-term reduction in the effort required to activate this key muscle.

Regarding kinematic performance, movement smoothness, as quantified by NMUs, showed a significant decrease immediately after the training ($p \leq 0.05$). However, there were no significant changes in the MTD at any of the time points after the training, suggesting that the program did not significantly alter compensatory trunk movements. A summary of the statistical comparisons for these EMG and kinematic parameters is available in Table 4.3.

Table 4.3 Normalized EMG activation level, normalized EMG CI, NMUs, and MTD at pre-, post-, 3MFU, and 6MFU assessments.

EMG parameters	Pre	Post	3MFU	6MFU	One-way repeated ANOVA	Friedman test
	Mean value (95% confidence interval)				*p* (Partial η^2)	*p* (Kendall's W)
Normalized EMG activation level						
ECU-ED	0.09(0.07~0.12)	0.08(0.06~0.10)	0.09(0.07~0.10)	0.07(0.06~0.09)		0.618(0.015)
APB	0.08(0.06~0.10)	0.08(0.05~0.10)	0.07(0.06~0.09)	0.05(0.04~0.06)		0.088(0.055)
TRI	0.06(0.05~0.08)	0.07(0.05~0.08)	0.06(0.05~0.07)	0.05(0.04~0.07)		0.423(0.023)
BIC	0.09(0.07~0.11)	0.07(0.05~0.08)	0.06(0.05~0.07)	0.06(0.05~0.08)		0.221(0.037)

FCR-FD	0.09(0.07~0.11)	0.07(0.06~0.08)	0.06(0.05~0.08)	0.05(0.04~0.06)		0.012* (0.091)
Normalized co-contraction index						
ECU-ED/APB	0.05(0.04~0.06)	0.04(0.03~0.05)	0.05(0.04~0.06)	0.04(0.03~0.05)		0.024* (0.079)
ECU-ED/FCR-FD	0.06(0.05~0.06)	0.05(0.04~0.06)	0.05(0.04~0.06)	0.04(0.03~0.05)		0.010** (0.095)
ECU-ED/BIC	0.06(0.05~0.07)	0.04(0.03~0.05)	0.05(0.04~0.06)	0.05(0.04~0.05)		0.115(0.049)
ECU-ED/TRI	0.05(0.04~0.06)	0.05(0.04~0.06)	0.05(0.04~0.06)	0.04(0.03~0.05)		0.695(0.012)
FCR-FD/APB	0.05(0.04~0.07)	0.05(0.04~0.05)	0.04(0.03~0.05)	0.03(0.02~0.04)		0.018* (0.084)
FCR-FD/BIC	0.05(0.04~0.06)	0.04(0.04~0.05)	0.04(0.03~0.05)	0.03(0.03~0.04)		0.035* (0.072)
FCR-FD/TRI	0.05(0.04~0.06)	0.05(0.04~0.06)	0.04(0.03~0.05)	0.03(0.03~0.04)		0.252(0.034)
APB/BIC	0.05(0.04~0.06)	0.04(0.03~0.05)	0.04(0.03~0.05)	0.03(0.03~0.04)		0.015* (0.087)
APB/TRI	0.05(0.04~0.06)	0.04(0.03~0.05)	0.04(0.03~0.05)	0.03(0.02~0.04)		0.466(0.021)
BIC/TRI	0.05(0.04~0.06)	0.04(0.03~0.05)	0.04(0.03~0.05)	0.04(0.03~0.05)		0.927(0.004)
Kinematic parameters						
NMUs	32.77 (27.75~37.78)	24.50 (20.72~28.28)	29.40 (25.04~33.77)	28.08 (23.72~32.45)		0.010** (0.095)
MTD	177.70 (158.27~197.12)	178.63 (160.47~196.78)	161.89 (142.53~181.25)	159.87 (139.26~180.49)	0.005** (0.104)	

The superscript "*" indicates a significant difference, with 1 superscript denoting $p \leq 0.05$ and 2 superscripts denoting $p \leq 0.01$.

4.5 Discussion

4.5.1 Self-help WH-ENMS-assisted telerehabilitation led to long-term rehabilitative benefits

This single-group study indicates that self-help WH-ENMS-assisted telerehabilitation yields enduring improvements in upper limb motor function among individuals with chronic stroke. The program enhanced motor function across the entire upper limb, as indicated by the FMA-UE, FMA shoulder/elbow, FMA wrist/hand, and ARAT scores

(Figure 4.3a). Significantly, improvements in proximal upper limb function (FMA shoulder/elbow) were maintained for up to six months after training (Figure 4.3a). Unlike some prior studies [35, 67], this intervention also led to improvements in ADLs, with significant gains in the WMFT score, WMFT time, and FIM scores that were sustained for six months (Figure 4.3a). This suggests that the skills learned during rehabilitation generalize into participants' daily routines. Evidence suggests that following intensive therapy, patients exhibit increased hand use across multiple tasks, with effects lasting up to one year [156]. Moreover, conducting RAT in the home setting offers distinct advantages over conventional center-based therapy in clinical environments. The familiarity and comfort of home environments facilitated greater compliance of individual patients to a long-term training program, which is fundamental to achieving motor restoration poststroke [97]. Conversely, self-help home-based rehabilitation facilitated the generalization of acquired motor skills to daily activities, as reflected in the functional gains observed at the 3MFU and 6MFU in this study. Consequently, incorporating home-based rehabilitation as a complement to conventional center-based, face-to-face clinical services may enhance overall rehabilitation outcomes.

4.5.2 Decreased muscular compensation and enhanced voluntary motor coordination in chronic stroke

The long-term improvements were also reflected in objective measures, including a

reduction in muscular compensation and improved voluntary coordination. The EMG CI showed sustained decreases between key muscle pairs (Figure 4.3b), indicating improved independence and less compensatory muscle activity. The reduced activation level of the FCR-FD muscle over six months (Figure 4.3c), for example, suggests a decrease in spasticity, which correlates with the sustained reductions in MAS wrist scores (Figure 4.3a). Kinematic data further confirmed this, with decreased NMUs pointing to smoother movement and better voluntary coordination (Figure 4.3d). The long-lasting effects observed in this study contrast with previous findings where some post-intervention gains did not persist [148]. This could be due to the unique design of the WH-ENMS, which integrates NMES and robotics to promote near-normal muscular coordination while actively suppressing compensatory movements. As a result, it yielded better motor outcomes and faster recovery compared to those using robots or NMES only [112, 113]. The system requires active engagement of the distal muscles (FCR-FD and ECU-ED), which are typically prone to compensation by proximal muscles [157]. This ensures that participants actively trigger the system through their own motor efforts, reinforcing correct muscle activation patterns.

Home-based telerehabilitation also addresses a major challenge of conventional therapy, i.e., the demand for one-on-one, in-person supervision. This model allows therapists to remotely oversee multiple patients, potentially leading to a more cost-effective service, a topic for future large-scale clinical trials. The success of this approach is contingent

on proper training of non-professionals (patients and caregivers) and robust remote monitoring. In this study, all participants were effectively trained during initial guided sessions, and their protocol adherence was tracked remotely through the WH-ENMS log data [67], ensuring the quality of the home-based training.

4.6 Periodic summary

Chapter 4 investigated the long-term effects of a robot-assisted telerehabilitation program using a mobile WH-ENMS with chronic stroke survivors. Employing a single-group pre-post design with follow-up assessments at three and six months, the study demonstrated that WH-ENMS-assisted telerehabilitation can yield sustained rehabilitative benefits lasting at least six months. These outcomes were corroborated by significant improvements in upper limb motor function, reduction in wrist and finger spasticity, enhanced functional independence, and better muscular coordination. The findings support the integration of such robot-assisted, home-based programs as a valuable and sustainable complement to conventional stroke rehabilitation services.

CHAPTER 5

CONCLUSIONS

Stroke is a growing global health challenge that leads to profound and lasting motor disability. Conventional rehabilitation models remain fundamentally misaligned with the biological requirements for neuroplasticity, as they often fail to provide the high-intensity, long-term therapy needed by stroke survivors living with residual motor impairments after discharge. Telerehabilitation has emerged as a promising paradigm to address barriers such as transportation limitations and shortages of rehabilitation professionals. Within this paradigm, RAT offers unique advantages by delivering repetitive, intensive practice with direct physical assistance. Despite its potential, existing robotic systems face an unresolved trade-off between logistical accessibility and therapeutic efficacy, and the critical role of remote management in sustaining patient engagement and ensuring long-term outcomes has received little attention. These challenges have hindered the integration of RAT into both clinical services and home-based rehabilitation, leaving its real-world feasibility and effectiveness uncertain.

To address this gap, this study explored the potential of RAT for stroke telerehabilitation through three studies: (1) development and validation of an Io-ENMS framework for home-based RAGT to maintain patient engagement and promote gait restoration; (2) clinical translation of a WH-ENMS-assisted telerehabilitation program for upper-limb recovery, assessing feasibility and comparing effectiveness between laboratory and

clinical implementations; (3) long-term evaluation of WH-ENMS-assisted telerehabilitation with 6MFU to assess the sustainability of upper-limb recovery.

In the first study, a novel Io-ENMS framework integrating IoT and ENMS was developed for robot-assisted telerehabilitation, enabling remote therapist supervision, cyber interaction among stroke users, and management of training progress based on the digital cyber networks. The system was validated in a telerehabilitation program consisting of 20 sessions of RAGT in home environments. The results demonstrated its feasibility and effectiveness in maintaining patient engagement and improving lower-limb motor function and gait patterns.

In the second study, a telerehabilitation program assisted by the WH-ENMS was translated from the laboratory into clinical service in a public hospital. The comparison between clinic and lab settings was conducted through a non-randomized controlled trial. The results revealed that the telerehabilitation program was feasible and effective for upper-limb recovery when translated into routine practice; however, its efficacy was compromised compared to the lab setting. This may be attributed to variations in compensatory strategies, quality of patient-operator interaction, and patient perceived usability in real-world contexts.

In the third study, long-term rehabilitative effects of the WH-ENMS-assisted telerehabilitation program were investigated through a single-group trial with 6MFU in individuals with chronic stroke. The results confirmed that the telerehabilitation

program supported durable improvements in upper-limb motor function, attributable to reduced compensatory movements and enhanced voluntary coordination in individuals with chronic stroke.

In summary, this study highlights the often-overlooked logistical management of telerehabilitation across diverse scenarios. First, this study developed and validated the feasibility of the Io-ENMS framework, which supports therapist supervision and patient interaction, while also providing insights into quantitative patient needs and safety control during home-based RAGT. Second, the successful translation of robot-assisted telerehabilitation from laboratory to clinical service underscored its feasibility to integrate into real-world practice, and identified logistical factors, such as patient-operator interaction and compensatory strategies, that warrant further optimization to achieve comparable results before broader implementation. Finally, the evidence of long-term functional benefits demonstrated the promise of RAT as a viable method of sustained clinical services. Collectively, these findings pave the way for the practical implementation of robot-assisted telerehabilitation, enabling sustained, accessible, and effective rehabilitation for stroke survivors.

In the future, further research will be conducted to:

1) explore the personalization of RAT to optimize training performance by tailoring robotic assistance and training intensity to the individual motor status and recovery trajectory of each patient.

2) conduct a large-scale RCT to evaluate the therapeutic benefits of RAT compared with conventional service, and examine cost-effectiveness, providing robust evidence for healthcare decision-making and policy adoption.

3) integrate automatic, home-based remote assessments for continuous monitoring of training quality and functional progress, enabling clinicians to tailor interventions dynamically and ensuring timely adjustments in therapy.

4) develop AI-driven chatbots to support patient engagement and self-management by providing motivational feedback and assisting with routine management, thereby reducing the burden on clinicians while improving adherence and satisfaction.

APPENDICES

Appendices A: Clinical Assessments for Upper Extremity

A-1: Mini-Mental State Examination (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)

Instructions for administration and scoring of the MMSE

Orientation (10 points):

- Ask for the date. Then specifically ask for parts omitted (e.g., "Can you also tell me what season it is?"). One point for each correct answer.
- Ask in turn, "Can you tell me the name of this hospital (town, county, etc.)?" One point for each correct answer.

Registration (3 points):

- Say the names of three unrelated objects clearly and slowly, allowing approximately one second for each. After you have said all three, ask the patient to repeat them. The number of objects the patient names correctly upon the first repetition determines the score (0-3). If the patient does not repeat all three objects the first time, continue saying the names until the patient is able to repeat all three items, up to six trials. Record the number of trials it takes for the patient to learn the words. If the patient does not eventually learn all three, recall cannot be meaningfully tested.
- After completing this task, tell the patient, "Try to remember the words, as I will ask for them in a little while."

Attention and Calculation (5 points):

- Ask the patient to begin with 100 and count backward by sevens. Stop after five subtractions (93, 86, 79, 72, 65). Score the total number of correct answers.
- If the patient cannot or will not perform the subtraction task, ask the patient to spell the word "world" backwards. The score is the number of letters in correct order (e.g., dlrow=5, dlorw=3).

Recall (3 points):

- Ask the patient if he or she can recall the three words you previously asked him or her to remember. Score the total number of correct answers (0-3).

Language and Praxis (9 points):

- Naming: Show the patient a wrist watch and ask the patient what it is. Repeat with a pencil. Score one point for each correct naming (0-2).
- Repetition: Ask the patient to repeat the sentence after you ("No ifs, ands, or buts."). Allow only one trial. Score 0 or 1.
- 3-Stage Command: Give the patient a piece of blank paper and say, "Take this paper in your right hand, fold it in half, and put it on the floor." Score one point for each part of the command correctly executed.
- Reading: On a blank piece of paper print the sentence, "Close your eyes," in letters large enough for the patient to see clearly. Ask the patient to read the sentence and do what it says. Score one point only if the patient actually closes his or her eyes. This is not a test of memory, so you may prompt the patient to "do what it says" after the patient reads the sentence.
- Writing: Give the patient a blank piece of paper and ask him or her to write a sentence for you. Do not dictate a sentence; it should be written spontaneously. The sentence must contain a subject and a verb and make sense. Correct grammar and punctuation are not necessary.
- Copying: Show the patient the picture of two intersecting pentagons and ask the patient to copy the figure exactly as it is. All ten angles must be present and two must intersect to score one point. Ignore tremor and rotation.

(Folstein, Folstein & McHugh, 1975)

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:

- Crum RM, Anthony JC, Bassett SS, Folstein MF. Population-based norms for the mini-mental state examination by age and educational level. *JAMA*. 1993;269(18):2386-2391.
- Folstein MF, Folstein SE, McHugh PR. "Mini-mental state": a practical method for grading the cognitive state of patients for the clinician. *J Psychiatr Res*. 1975;12:189-198.
- Rovner BW, Folstein MF. Mini-mental state exam in clinical practice. *Hosp Pract*. 1987;22(1A):99, 103, 106, 110.
- Tombaugh TN, McIntyre NJ. The mini-mental state examination: a comprehensive review. *J Am Geriatr Soc*. 1992;40(9):922-935.

A-2: Modified Ashworth Scale (MAS)

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.

Modified Ashworth Scale Testing Form

Name:_____ Date:_____

Muscle Tested	Score
_____	____
_____	____
_____	____
_____	____
_____	____
_____	____
_____	____
_____	____
_____	____

Reference for test instructions:

Bohannon, R. and Smith, M. (1987). "Interrater reliability of a modified Ashworth scale of muscle spasticity." Physical Therapy 67(2): 206.

A-3: Fugl-Meyer Assessment for Upper Extremity (FMA-UE)

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 Elbow Forearm	retraction elevation abduction (90°) external rotation flexion supination	0 0 0 0 0 0	1 1 1 1 1 1	2 2 2 2 2 2
	Shoulder Elbow Forearm	adduction/internal rotation extension pronation	0 0 0	1 1 1	2 2 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 neutral	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			**hyper**	**lively**	**normal**
Biceps, triceps, finger flexors	2 of 3 reflexes markedly hyperactive 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)			

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		0	1	2
Dysmetria	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	6 or more 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)	

A-4: Action Research Arm Test (ARAT)

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	

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

References

Carroll D. "A quantitative test of upper extremity function."
J Chronic Diseases. 1965;18:479-491.

Crow JL, Lincoln NNB, Nouri FM, De Weerdt W. "The effectiveness of EMG biofeedback in the treatment of arm function after stroke.
International Disability Studies. 1989;11:155-160.

De Weerdt WJG, Harrison MA. "Measuring recovery of arm-hand function in stroke patients: a comparison of the Brunnstrom-Fugl-Meyer test and the Action Research Arm test.
Physiotherapy Canada. 1985;37:65-70.

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***Int J Rehabil Res*. 1981;4:483-492.**

A-5: Functional Independence Measure (FIM)

	ADMISSION	DISCHARGE	FOLLOW-UP
Self-Care			
A. Eating			
B. Grooming			
C. Bathing			
D. Dressing - Upper Body			
E. Dressing - Lower Body			
F. Toileting			
Sphincter Control			
G. Bladder Management			
H. Bowel Management			
Transfers			
I. Bed, Chair, Wheelchair			
J. Toilet			
K. Tub, Shower			
Locomotion			
L. Walk/Wheelchair			
M. Stairs			
Motor Subtotal Score			
Communication			
N. Comprehension			
O. Expression			
Social Cognition			
P. Social Interaction			
Q. Problem Solving			
R. Memory			
Cognitive Subtotal Score			
TOTAL FIM Score			

LEVELS	**Independent** 7 Complete Independence (Timely, Safely) 6 Modified Independence (Device)	**NO HELPER**
	Modified Dependence 5 Supervision (Subject = 100%+) 4 Minimal Assist (Subject = 75%+) 3 Moderate Assist (Subject = 50%+) **Complete Dependence** 2 Maximal Assist (Subject = 25%+) 1 Total Assist (Subject = less than 25%)	**HELPER**
Note: Leave no blanks. Enter 1 if patient is not testable due to risk.		

A-6: Wolf Motor Function Test (WMFT)

Type/Purpose of Test: The purpose of this test is to quantify upper extremity UE motor ability through a series of timed and functional tasks.

Population: Used primarily for stroke patients but could be used for people with impaired UE motor ability. *Limited usefulness for patients with chronic stroke and TBI who are lower functioning in motor deficit. Or for acute or sub-acute stroke before spontaneous recovery has completed.

Focus of measurement:
___Organic systems (X)Abilities ___Participation/life habits ___Environmental Factors

Ease of Administration:
General Description of the WMFT
All tasks are performed as quickly as possible and are truncated at
120 seconds. Tasks are as follows:
1. Forearm to table (side): Subject attempts to place forearm on the table by abduction at the shoulder.
2. Forearm to box (side): Subject attempts to place a forearm on the box by abduction at the shoulder.
3. Extend elbow (side): Subject attempts to reach across the table by extending the elbow (to the side).
4. Extend elbow (to the side), with weight: Subject attempts to push the sandbag against outer wrist joint across the table by extending the elbow.
5. Hand to table (front): Subject attempts to place involved hand on the table.
6. Hand to box (front): Subject attempts to place hand on the box.
7. Reach and retrieve (front): Subject attempts to pull 1-lb weight across the table by using elbow flexion and cupped wrist.
8. Lift can (front): Subject attempts to lift can and bring it close to lips with a cylindrical grasp.
9. Lift pencil (front): Subject attempts to pick up pencil by using 3-jaw chuck grasp
10. Pick up paper clip (front): Subject attempts to pick up paper clip by using a pincer grasp.
11. Stack checkers (front): Subject attempts to stack checkers onto the center checker.
12. Flip cards (front): Using the pincer grasp, patient attempts to flip each card over.
13. Turning the key in lock (front): Using pincer grasp, while maintaining contact, patient turns key fully to the left and right.
14. Fold towel (front): Subject grasps towel, folds it lengthwise, and then uses the tested hand to fold the towel in half again.
15. Lift basket (standing): Subject picks up basket by grasping the handles and placing it on bedside table.

Clarity of Directions:
Very clear and easy to follow directions for the administrator of the test and the test taker.

Scoring Procedures:
The speed at which functional tasks can be completed is measured by performance time and the movement quality when completing the tasks is measured by functional ability.
Speed is measured by timing the task with a stopwatch from start to finish.
Movement quality during the task is measured by functional ability using a 6-point ordinal scale, where 0 = does not attempt with the involved arm and 5 = arm does participate/movement appears to be normal.

Examiner Qualification & Training
No qualification or training required.

Standardization: ____ **Norms** ____ **Criterion Referenced** ____ **Other** **None were mentioned in the manual.**

Reliability: The inter-test and inter-rater reliability, and internal consistency and stability of the test is high for both the performance time and Functional Ability rating scale measures, ranging from .88 to .98, with most values ≈ .95

Validity: Construct validity, criterion validity

Manual: ____ **Excellent** **(X) Adequate** ____ **Poor**

What is (are) the setting/s that you would anticipate using this assessment?
I could see this used in any setting where a person with a stroke or UE motor impairment is being treated. Inpatient, outpatient, home health, related research, etc. (acute rehab might be a little premature for this type of test.)

Summary of strengths and weaknesses:

Weakness:

I think that it is very easy for interraters to be consistent with the timing part of the test but I think there could be some difference of opinion for the movement quality assessment. A patient could become very frustrated if they were not able to do well in a timed test environment.

Strength:

There are mostly functional measurements of UE use. It is something that can be used to track progress of a patient. Very easy to learn and administer. Not expensive to simulate in a clinic or wherever you want to use it.

Appendices B: Clinical Assessments for Lower Extremity

B-7: Functional Ambulatory Category (FAC)

Name: Gender: Date: Assessor:

Appendix—Description of Functional Ambulation Category (FAC)

FAC	Ambulation Description	Definition
0	Nonfunctional ambulation	Subject cannot ambulate, ambulates in parallel bars only, or requires supervision or physical assistance from more than one person to ambulate safely outside of parallel bars
1	Ambulator-Dependent for Physical Assistance Level II	Subject requires manual contacts of no more than one person during ambulation on level surfaces to prevent falling. Manual contacts are continuous and necessary to support body weight as well as maintain balance and/or assist coordination
2	Ambulator-Dependent for Physical Assistance Level I	Subject requires manual contact of no more than one person during ambulation on level surfaces to prevent falling. Manual contact consists of continuous or intermittent light touch to assist balance or coordination
3	Ambulator-Dependent for Supervision	Subject can physically ambulate on level surfaces without manual contact of another person but for safety requires standby guarding on no more than one person because of poor judgment, questionable cardiac status, or the need for verbal cuing to complete the task.
4	Ambulator-Independent Level Surfaces only	Subject can ambulate independently on level surfaces but requires supervision or physical assistance to negotiate any of the following: stairs, inclines, or non-level surfaces.
5	Ambulator-Independent	Subject can ambulate independently on nonlevel and level surfaces, stairs, and inclines.

B-8: Berg Balance Scale (BBS)

BERG BALANCE TEST

Name: _____ Date: _____

Age: ____ Sex: ____ Diagnosis: _____

Contact no.: _____ Address: _____

Location: _____ Rater: _____

S.N.	Item Description	Date				
		Score [0-4]				
1	Sit to stand					
2	Standing Unsupported					
3	Sitting Unsupported					
4	Standing to sitting					
5	Transfers					
6	Standing with eyes closed					
7	Standing with feet together					
8	Reaching forward with outstretched arms					
9	Retrieving object from ground					
10	Turning to look behind					
11	Turning 360 degrees					
12	Placing alternate foot on stool					
13	Standing with one foot in front					
14	Standing on one foot					
	Total					

Interpretation

- 0–20 : Wheelchair bound
- 21–40 : Walking with assistance
- 41–56 : Independent

Berg Balance Scale (with instructions)

SITTING TO STANDING
INSTRUCTIONS: Please stand up. Try not to use your hand for support.
( ) 4 able to stand without using hands and stabilize independently
( ) 3 able to stand independently using hands
( ) 2 able to stand using hands after several tries
( ) 1 needs minimal aid to stand or stabilize
( ) 0 needs moderate or maximal assist to stand

STANDING UNSUPPORTED
INSTRUCTIONS: Please stand for two minutes without holding on.
( ) 4 able to stand safely for 2 minutes
( ) 3 able to stand 2 minutes with supervision
( ) 2 able to stand 30 seconds unsupported
( ) 1 needs several tries to stand 30 seconds unsupported
( ) 0 unable to stand 30 seconds unsupported

If a subject is able to stand 2 minutes unsupported, score full points for sitting unsupported. Proceed to item #4.

SITTING WITH BACK UNSUPPORTED BUT FEET SUPPORTED ON FLOOR OR ON A STOOL
INSTRUCTIONS: Please sit with arms folded for 2 minutes.
( ) 4 able to sit safely and securely for 2 minutes
( ) 3 able to sit 2 minutes under supervision
( ) 2 able to able to sit 30 seconds
( ) 1 able to sit 10 seconds
( ) 0 unable to sit without support 10 seconds

STANDING TO SITTING
INSTRUCTIONS: Please sit down.
( ) 4 sits safely with minimal use of hands
( ) 3 controls descent by using hands
( ) 2 uses back of legs against chair to control descent
( ) 1 sits independently but has uncontrolled descent
( ) 0 needs assist to sit

TRANSFERS
INSTRUCTIONS: Arrange chair(s) for pivot transfer. Ask subject to transfer one way toward a seat with armrests and one way toward a seat without armrests. You may use two chairs (one with and one without armrests) or a bed and a chair.
( ) 4 able to transfer safely with minor use of hands
( ) 3 able to transfer safely definite need of hands
( ) 2 able to transfer with verbal cuing and/or supervision
( ) 1 needs one person to assist
( ) 0 needs two people to assist or supervise to be safe

STANDING UNSUPPORTED WITH EYES CLOSED
INSTRUCTIONS: Please close your eyes and stand still for 10 seconds.
( ) 4 able to stand 10 seconds safely
( ) 3 able to stand 10 seconds with supervision
( ) 2 able to stand 3 seconds
( ) 1 unable to keep eyes closed 3 seconds but stays safely
( ) 0 needs help to keep from falling

STANDING UNSUPPORTED WITH FEET TOGETHER
INSTRUCTIONS: Place your feet together and stand without holding on.
( ) 4 able to place feet together independently and stand 1 minute safely
( ) 3 able to place feet together independently and stand 1 minute with supervision
( ) 2 able to place feet together independently but unable to hold for 30 seconds

( ) 1 needs help to attain position but able to stand 15 seconds feet together
( ) 0 needs help to attain position and unable to hold for 15 seconds

REACHING FORWARD WITH OUTSTRETCHED ARM WHILE STANDING
INSTRUCTIONS: Lift arm to 90 degrees. Stretch out your fingers and reach forward as far as you can. (Examiner places a ruler at the end of fingertips when arm is at 90 degrees. Fingers should not touch the ruler while reaching forward. The recorded measure is the distance forward that the fingers reach while the subject is in the most forward lean position. When possible, ask subject to use both arms when reaching to avoid rotation of the trunk.)
( ) 4 can reach forward confidently 25 cm (10 inches)
( ) 3 can reach forward 12 cm (5 inches)
( ) 2 can reach forward 5 cm (2 inches)
( ) 1 reaches forward but needs supervision
( ) 0 loses balance while trying/requires external support

PICK UP OBJECT FROM THE FLOOR FROM A STANDING POSITION
INSTRUCTIONS: Pick up the shoe/slipper, which is place in front of your feet.
( ) 4 able to pick up slipper safely and easily
( ) 3 able to pick up slipper but needs supervision
( ) 2 unable to pick up but reaches 2-5 cm(1-2 inches) from slipper and keeps balance independently
( ) 1 unable to pick up and needs supervision while trying
( ) 0 unable to try/needs assist to keep from losing balance or falling

TURNING TO LOOK BEHIND OVER LEFT AND RIGHT SHOULDERS WHILE STANDING
INSTRUCTIONS: Turn to look directly behind you over toward the left shoulder. Repeat to the right. Examiner may pick an object to look at directly behind the subject to encourage a better twist turn.
( ) 4 looks behind from both sides and weight shifts well
( ) 3 looks behind one side only other side shows less weight shift
( ) 2 turns sideways only but maintains balance
( ) 1 needs supervision when turning
( ) 0 needs assist to keep from losing balance or falling

TURN 360 DEGREES
INSTRUCTIONS: Turn completely around in a full circle. Pause. Then turn a full circle in the other direction.
( ) 4 able to turn 360 degrees safely in 4 seconds or less
( ) 3 able to turn 360 degrees safely one side only 4 seconds or less
( ) 2 able to turn 360 degrees safely but slowly
( ) 1 needs close supervision or verbal cuing
( ) 0 needs assistance while turning

PLACE ALTERNATE FOOT ON STEP OR STOOL WHILE STANDING UNSUPPORTED
INSTRUCTIONS: Place each foot alternately on the step/stool. Continue until each foot has touch the step/stool four times.
( ) 4 able to stand independently and safely and complete 8 steps in 20 seconds
( ) 3 able to stand independently and complete 8 steps in > 20 seconds
( ) 2 able to complete 4 steps without aid with supervision
( ) 1 able to complete > 2 steps needs minimal assist
( ) 0 needs assistance to keep from falling/unable to try

STANDING UNSUPPORTED ONE FOOT IN FRONT
INSTRUCTIONS: (DEMONSTRATE TO SUBJECT) Place one foot directly in front of the other. If you feel that you cannot place your foot directly in front, try to step far enough ahead that the heel of your forward foot is ahead of the toes of the other foot. (To score 3 points, the length of the step should exceed the length of the other foot and the width of the stance should approximate the subject's normal stride width.)
( ) 4 able to place foot tandem independently and hold 30 seconds
( ) 3 able to place foot ahead independently and hold 30 seconds
( ) 2 able to take small step independently and hold 30 seconds
( ) 1 needs help to step but can hold 15 seconds
( ) 0 loses balance while stepping or standing

STANDING ON ONE LEG

INSTRUCTIONS: Stand on one leg as long as you can without holding on.

( ) 4 able to lift leg independently and hold > 10 seconds
( ) 3 able to lift leg independently and hold 5-10 seconds
( ) 2 able to lift leg independently and hold ≥ 3 seconds
( ) 1 tries to lift leg unable to hold 3 seconds but remains standing independently.
( ) 0 unable to try of needs assist to prevent fall

( ) TOTAL SCORE (Maximum = 56)

B-9: Fugl-Meyer Assessment for Lower Extremity (FMA-LE)

FMA-LE PROTOCOL

FUGL-MEYER ASSESSMENT
LOWER EXTREMITY (FMA-LE)
Assessment of sensorimotor function

Fugl-Meyer AR, Jaasko L, Leyman I, Olsson S, Steglind S: The post-stroke hemiplegic patient. 1. a method for evaluation of physical performance. Scand J Rehabil Med 1975, 7:13-31.

E. LOWER EXTREMITY					
I. Reflex activity, supine position			**none**	**can be elicited**	
Flexors: knee flexors			0	2	
Extensors: patellar, achilles (at least one)			0	2	
Subtotal I (max 4)					
II. Volitional movement within synergies supine position			**none**	**partial**	**full**
Flexor synergy: Maximal hip flexion (abduction/external rotation), maximal flexion in knee and ankle joint (palpate distal tendons to ensure active knee flexion).	Hip	flexion	0	1	2
	Knee	flexion	0	1	2
	Ankle	dorsiflexion	0	1	2
Extensor synergy: From flexor synergy to the hip extension/adduction, knee extension and ankle plantar flexion. Resistance is applied to ensure active movement, evaluate both movement and strength (compare with the unaffected side)	Hip	extension	0	1	2
		adduction	0	1	2
	Knee	extension	0	1	2
	Ankle	plantar flexion	0	1	2
Subtotal II (max 14)					
III. Volitional movement mixing synergies sitting position, knee 10cm from the edge of the chair/bed			**none**	**partial**	**full**
Knee flexion from actively or passively extended knee	no active motion less than 90° active flexion, palpate tendons of hamstrings more than 90° active flexion		0	1	2
Ankle dorsiflexion compare with unaffected side	no active motion limited dorsiflexion complete dorsiflexion		0	1	2
Subtotal III (max 4)					
IV. Volitional movement with little or no synergy standing position, hip at 0°			**none**	**partial**	**full**
Knee flexion to 90° hip at 0°, balance support is allowed	no active motion or immediate, simultaneous hip flexion less than 90° knee flexion and/or hip flexion during movement at least 90° knee flexion without simultaneous hip flexion		0	1	2
Ankle dorsiflexion compare with unaffected side	no active motion limited dorsiflexion complete dorsiflexion		0	1	2
Subtotal IV (max 4)					
V. Normal reflex activity supine position, assessed only if full score of 4 points is achieved in part IV, compare with the unaffected side			**hyper**	**lively**	**normal**
Reflex activity knee flexors, Patellar, Achilles,	2 of 3 reflexes markedly hyperactive 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 E (max 28)					

F. COORDINATION/SPEED, supine, after one trial with both legs, eyes closed, heel to knee cap of the opposite leg, 5 times as fast as possible		**marked**	**slight**	**none**
Tremor		0	1	2
Dysmetria	pronounced or unsystematic slight and systematic no dysmetria	0	1	2
		≥ 6s	**2 - 5s**	**< 2s**
Time	6 or more seconds slower than unaffected side 2-5 seconds slower than unaffected side less than 2 seconds difference	0	1	2
	Total F (max 6)			

H. SENSATION, lower extremity eyes closed, compare with the unaffected side		**anesthesia**	**hypoesthesia or dysesthesia**	**normal**
Light touch	leg foot sole	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	hip knee ankle great toe (IP-joint)	0 0 0 0	1 1 1 1	2 2 2 2
	Total H (max12)			

I. PASSIVE JOINT MOTION, lower extremity supine position, compare with the unaffected side					**J. JOINT PAIN** during passive motion, lower extremity		
		only few degrees (<10° hip)	decreased	normal	pronounced pain during movement or very marked pain at the end of the movement	some pain	no pain
Hip	Flexion	0	1	2	0	1	2
	Abduction	0	1	2	0	1	2
	External rotation	0	1	2	0	1	2
	Internal rotation	0	1	2	0	1	2
Knee	Flexion	0	1	2	0	1	2
	Extension	0	1	2	0	1	2
Ankle	Dorsiflexion	0	1	2	0	1	2
	Plantar flexion	0	1	2	0	1	2
Foot	Pronation	0	1	2	0	1	2
	Supination	0	1	2	0	1	2
Total (max 20)					**Total** (max 20)		

E. LOWER EXTERMTY	/28
F. COORDINATION / SPEED	/6
TOTAL E-F (motor function)	/34

H. SENSATION	/12
I. PASSIVE JOINT MOTION	/20
J. JOINT PAIN	/20

B-10: Modified Ashworth Scale (MAS)

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

Joints:

Hip:

Knee:

Ankle:

B-11: 10 Meter Walk Test (10MWT)

Core Measure: 10 Meter Walk Test (10mWT)

Overview	• The 10mWT is used to assess walking speed in meters/second (m/s) over a short distance.
Number of Test Items	• 1 item
Scoring	• The total time taken to ambulate 6 meters (m) is recorded to the nearest hundredth of a second. 6 m is then divided by the total time (in seconds) taken to ambulate and recorded in m/s[1,2]
Equipment	• Stopwatch • A clear pathway of at least 10 m (32.8 ft) in length in a designated area over solid flooring[2,3]
Time (new clinician) **Time (experienced clinician)**	• 5 minutes or less • 5 minutes or less
Cost	• Free
Logistics-Setup	• A clear pathway of at least 10 m (32.8 ft) in length in a designated area over solid flooring is required. • Measure and mark the start and end point of a 10-m walkway. • Add a mark at 2 m and 8 m (identifying the central 6 m which will be timed). • Quiet conditions[1]

Logistics-Administration	• Comfortable walking speed:
	  ○ Have the patient start on the 0-m mark (start line)
	  ○ Instructions to patient: *"Walk at your own comfortable walking pace and stop when you reach the far mark."*
	• Fast walking speed:
	  ○ Have the patient start on the 0-m mark (start line)
	  ○ Instructions to patient: *"Walk as fast as you can safely walk and stop when you reach the far mark."*
	• Two trials are administered at the patient's comfortable walking speed, followed by 2 trials at his/her fast walking speed, per the below instructions. The 2 trials, for each speed, are averaged and the 2 gait speeds are documented in meters/second.[1]
	• Patients may use any assistive device or bracing that they are currently using. The type of device and/or bracing must be documented.
	• When administering the test, do not walk in front of or directly beside the patient, as this may "pace" the patient and influence the speed and distance they walk. Instead, walk at least a half step behind the patient.

	• If a patient requires assistance, only the minimum amount of assistance required for a patient to complete the task should be provided. The level of assistance documented, however, should reflect the greatest amount of assistance provided during the test. For example, if a patient required minimum assistance for the majority of the test but required moderate assistance for stability on one occasion, the patient should be rated as requiring moderate assistance. Assistance should be provided to prevent a fall or collapsing (i.e. knee buckling, trunk collapse, etc). Assistance should not be provided for limb swing, or any other manner in which the assistance is propelling the patient forward. o The level of physical assistance documented using an ordinal 7-point scale is described below. 1 = *total assistance* [patient performs 0%-24% of task]* 2 = *maximum assistance* [patient performs 25%-49% of task] 3 = *moderate assistance* [patient performs 50%-74% of task] 4 = *minimum assistance* [patient performs 75%-99% of task] 5 = *supervision* [patient requires stand-by or set-up assistance; no physical contact is provided] 6 = *modified independent* [patient requires use of assistive devices or bracing, needs extra time, mild safety issues] 7 = *independent* ***Note:** if your patient requires *total assistance*, a score of 0 should be documented
Logistics-Scoring	• The time is measured for the middle 6 m to allow for patient acceleration and deceleration.[1,4] o The time is started when any part of the leading foot crosses the plane of the 2-m mark. o The time is stopped when any part of the leading foot crosses the plane of the 8-m mark.[1] • Document the time to walk the middle 6m, the level of assistance, and type of assistive device and/or bracing used. • If a patient requires *total assistance* or is unable to ambulate at all, a score of 0 m/s should be documented.
Additional Recommendations	• Patients should not talk during the test, as this depletes their respiratory reserves. Exceptions to this are if the patient requests to stop the test or needs to report any symptoms (e.g. pain, dizziness). • The person administering the test also should not talk. Talking during the test can distract the patient and affect their score on the test. • For patients who are unable to walk, but have a goal and the capacity to achieve walking, a baseline score of 0 meters/second should be documented. • To track change, it is recommended that this measure is administered a minimum of two times (admission and discharge), and when feasible, between these periods, under the same test conditions for the patient.

	• Recommend review of this standardized procedure and, on an annual basis, establish consistency within and among raters using the tool.

Common Questions and Variations

1. "What if I don't have 10 open meters to do the assessment?"
    a. Variations to the 10mWT exist, including the 5MWT. Clinical recommendations include a "rolling start and finish" during the 5MWT to allow for acceleration and deceleration. It is important to note that the 5MWT has not been validated in as many health conditions as the 10mWT.[4,5]
    b. Individuals or organizations should use the 10mWT standardized protocol to assess aggregate data for their patients. In cases when the protocol cannot be used, the modifications to the administration process should be documented.

2. "My patient requires contact guard assistance, can I still administer this measure?"
    a. Yes, If physical assistance is needed for a patient to complete the 10mWT please document the time (m/s), the level of assistance provided, and the assistive device or bracing used.
    b. The level of physical assistance required should be documented using an ordinal 7-point scale described below.
        1 = *total assistance* [patient performs 0%-24% of task]*
        2 = *maximum assistance* [patient performs 25%-49% of task]
        3 = *moderate assistance* [patient performs 50%-74% of task]
        4 = *minimum assistance* [patient performs 75%-99% of task]
        5 = *supervision* [patient requires stand-by or set-up assistance; no physical contact is provided]
        6 = *modified independent* [patient requires use of assistive devices or bracing, needs extra time, mild safety issues]
        7 = *independent*
        ***Note:** if your patient requires *total assistance*, a score of 0 should be documented
    c. It is important to note that the assisted test may not be directly comparable to the distance that patient walks without assistance, and it may not be compared to published normative values.

3. "What if it is not clinically feasible to complete two trials of each condition, comfortable and fast walking speed?"
    a. If four test trials are not clinically feasible, it is recommended that two trials, one trial at a comfortable and one at a fast walking speed, be performed to provide an assessment of the patient's ability to alter gait speed.
    b. If two trials are not clinically feasible, it is recommended that a trial of comfortable walking speed be prioritized. Consider that if a patient has goals to return to the community, the assessment of fast walking speed has more value. If a patient has the ability to walk fast, he/she may be able to more fully participate in the

community and adapt to environmental context. If the projected outcome for the patient is community ambulation, a fast gait speed should be collected at the earliest time point possible, and re-testing is recommended to track change.

4. "My patient has impaired cognition and gets distracted during the test, frequently forgetting what their goal is. Can I still administer this measure?"
    a. Yes. Examiners can use brief verbal, visual, or tactile cues to keep a patient on-task and to remind him/her of the goal, but be consistent (e.g., "Keep going. Walk to the mark."). Document the type and frequency of the required cues.

5. "Can the patient use an assistive device during the test?"
    a. Yes, the patient can use an assistive device during the test. Recommendations include documenting the assistive device and keeping the assistive device consistent between trials and reassessments.
    b. Inappropriate assistive devices can have a negative impact on walking speed and therefore reduce the validity of the test.[2] It is likely that the type of assistive device a patient needs may change over time. If/when a different assistive device is indicated, the reason behind a different device choice should be noted.
    c. If the patient no longer needs the assistive device, or has progressed to a less restrictive device, it would be appropriate to repeat the test with this change in conditions and document this fact.
    d. It is appropriate to have the patient utilize the assistive device which he/she is most likely to use in his/her own environment.

6. "Can the patient use orthoses or bracing during the test?"
    a. Yes, the patient should wear the walking devices necessary for ambulation (AFO, KAFO, Neuroprostheses, etc). The walking device should be documented and kept consistent between trials and assessments.[6]
    b. If the patient no longer needs the orthosis which was used in the initial test, it is appropriate to repeat the test without the orthosis and document this fact.
    c. It is appropriate to have the patient utilize the orthosis or brace which he/she is most likely to use in his/her own environment.

7. "Where should the therapist stand and guard?"
    a. Standing behind the patient will reduce the likelihood of the clinician setting the pace and will also keep the clinician and stopwatch out of sight of the patient to reduce the likelihood of the patient "racing."[2]

8. "Should I count the number of steps taken to complete the 10mWT?"
    a. You can! The number steps to complete the test may provide insight into stride length. Although documenting this number may add individual value to specific clinical situations, there has not been extensive research validating the observational step count in various neurological conditions.[2]

9. "What if it is not clinically feasible to complete two trials of each condition, comfortable and fast walking speed?"
    a. If four test trials are not clinically feasible, it is recommended that two trials, one trial at a comfortable and one at a fast walking speed, be performed to provide an assessment of the patient's ability to alter gait speed.
    b. If two trials are not clinically feasible, it is recommended that a trial of comfortable walking speed be prioritized.
    c. Consider that if a patient has goals to return to the community, the assessment of fast walking speed has value. If a patient has the ability to walk fast, he/she may be able to more fully participate in the community and adapt to environmental context. If the projected outcome for the patient is community ambulation, a fast gait speed should be collected at the earliest time point possible, and re-testing is recommended to track change.

Appendices C: Research Materials for Chapter 2

C-12: Consent Form for Chapter 2

研究課題：外神經肌骨系統下肢康復隨機對照實驗

研究負責人： 潘偉生教授
醫療機構： 香港沙田威爾斯親王醫院腦神經外科
聯絡電話： (852) 3505 1316

知情同意書

我，_____(受試者姓名), 在此同意作為受試者參加 “外神經肌骨系統下肢康復隨機對照實驗” 。

- 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。
- 我已明白這是一個隨機對照實驗，我可能被分配在實驗組，亦可能在對照組。
- 我已明白這個實驗有可能可以改善我的下肢運動功能。
- 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。
- 為避免您在訓練中跌倒，我已明白在訓練中我可使用拐杖，指導員亦會全程在身邊指導保護我的安全。
- 我已知道這個測試的結果將被保存至少三年並可被發表, 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_____

C-13: Information Sheet for Chapter 2

研究資料單張

研究課題: 外神經肌骨系統下肢康復隨機對照實驗

研究負責人：潘偉生教授
醫療機構：香港沙田威爾斯親王醫院腦神經外科
聯絡電話：(852) 3505 1316

歡迎您參加由香港理工大學生物醫學工程學系研究人員以及**香港沙田威爾斯親王醫院腦神經外科**開展的外神經肌骨系統下肢復康隨機對照實驗。這個項目是為了研究中風後在外神經肌骨系統協助下進行復康訓練下肢功能的恢復效果。

在您決定參加之前請您瞭解這研究的內容。請仔細讀以下資訊和歡迎與朋友、親戚和您的家庭醫生談論。如有不清楚或您想要的更多資訊，請聯絡我們。想清楚後才決定是否參與。

試驗步驟：
在試驗開始之前，受試者將會被告知試驗內容並簽署知情同意書。這是一個隨機對照實驗，您可能被分配在實驗組，亦可能在對照組。若您被安排在外神經肌骨系統下肢康復訓練組，在訓練中，您將在患肢上佩戴外神經肌骨康復系統(見圖 1)，並在系統的幫助下以您的自然步速行走。若您被安排在對照訓練組，在訓練中，您將在沒有外神經肌骨康復系統協助下進行常規的下肢訓練。您會有二十堂訓練(60 分鐘/堂，3-5 堂/週)。

圖一 訓練系統

我們希望訓練將幫助到您的下肢功能康復。但是，這無法被保證。我們希望通過這項研究瞭解如何更有效的幫助中風患者康復。

在進行試驗之前和之後有技術員測試您的下肢活動功能。本訓練將不會給您帶來任何不適。為預防您在訓練中跌倒，我們將為您提供四腳拐杖（如有需要），同時亦

會有技術員全程陪同指導，保證您的安全。訓練之前和之後及三個月和六個月後都會進行評估。只有參與此項目的工作人員有權檢索和使用測試數據。這些測試資料將被保存至少三年，但所有與您有關的資訊將會用可識別的代碼保密。此項目由香港創新科技署資助。您有權力在訓練和測試中的任何時間決定中止試驗而不會受到任何處罰。如果您有什麼意見或者投訴，您可以聯絡香港中文大學 - 新界東醫院聯網臨床研究倫理聯席委員會 (Tel: 3505 3935)，或者聯絡本研究的副負責人胡曉翎博士(Tel: 3400 3206)。
謝謝！

C-14: AF-ENMS home-based user manuals

THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

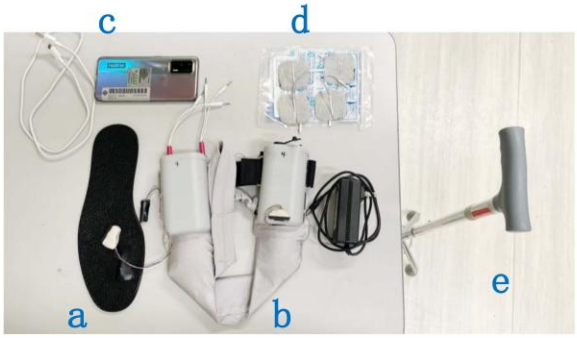
外神經肌骨系統使用手冊

1. 您在使用 ENMS 下肢康復機器時，必須在無障礙物的水準地面進行行路訓練（例如：走廊和運動場），必須使用我方提供的四角叉手仗輔助行路，以保證安全。
2. 您在使用此下肢康復機器行路訓練時，**必須有監護人全程陪護**（無需攙扶，保持 0.5 米距離），以應對可能出現的意外情況，如摔倒或身體不適。

   Tips: 若出現上述意外情況，監護人應立即扶穩患者，關閉機器電源，攙扶患者至附近安全處就坐休息，如需救助立即呼叫醫護救援，並通知研究人員（電話：　　後續跟進。
3. 在使用此下肢康復機器時，建議您穿著舒適的運動鞋，並準備兩張椅子，以備在訓練中途休息時使用。
4. 此外神經肌骨系統屬香港理工大學資產，租借期間請妥善保管，訓練結束時研究人員會收回所有設備。

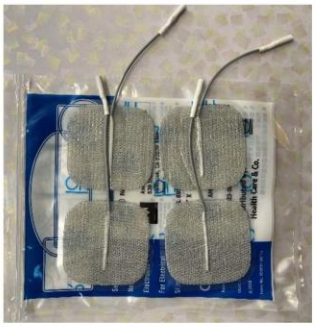
1

1. 包裝內容



a. 感測器鞋墊； b. 主機與充電器； c. 手機與充電線； d. 電刺激貼片； e. 四角叉手仗

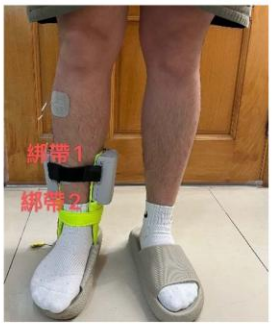
2. 穿戴流程



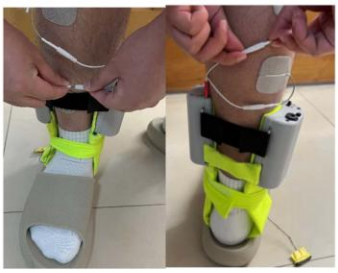
（1）取出可重複使用的電極貼片（4 片）

P. S. 每週換一次

（2）將電極貼片，貼在目標肌肉位置。具體位置以研究人員的指導為准。



（3）如圖將綁帶 1 和綁帶 2 的魔術貼扣緊，穿戴固定主機



（4）如圖將電刺激導線與電極貼片相連

（5）替換原鞋墊，將感測器鞋墊平整放入

（6）穿上鞋後，將兩片磁吸式埠相連

（7）開關撥至 ON 檔開啟電源，等待測試

3. 校準與訓練流程

將設備穿戴穩固後，可微調位置以保證穿戴的舒適性。

請確認設備電源已開啟，再打開“移動復康寶”應用程式。

（1）輸入研究人員分配的帳戶資料，登入系統。若忘記資料，請聯繫研究人員找回。

（2）登入系統後，點擊“下肢”按鈕。

（3）點擊右上角“ ”標誌，等待出現如圖的藍牙列表，選擇“Ankle”連接藍牙。

（4）確認“已連接裝置”，“校準資料已完整”後，點擊“開始訓練”按鈕。

Tips:若出現“未連接裝置”，請重複步驟（3），若出現“校準資料不完整”，請聯繫研究人員。

（5）等待校準資料傳輸至設備，調整好站姿後，點擊“開始訓練”。

（6）訓練一段时间后，點擊“暫停”按鈕，坐下休息 5 分鐘。

（7）休息結束後，起身調整好站姿，點擊“繼續”按鈕恢復訓練。完成後點擊“**結束訓練**”按鈕。

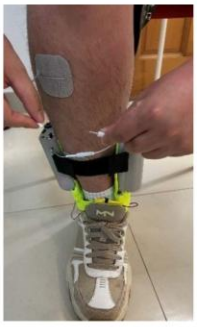
注意：

- 訓練中途，請保持手機螢幕常亮，不要觸碰螢幕，以免切換到其它應用程式。
- 訓練中途若感到不適，可點擊“暫停”按鈕中斷訓練。

4. 拆卸流程

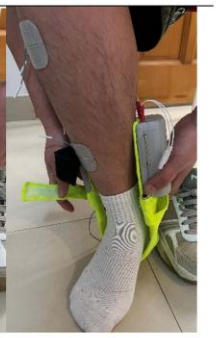
訓練結束後，請移步至安全地帶坐下，完成以下拆卸流程。

1. 開關撥至“OFF”檔關閉電源



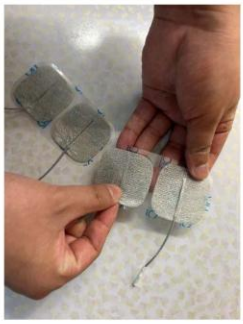
2. 拔開電刺激導線和電極貼片的連接（前後4處），拔開磁性式埠。

3. 手扶主機兩側，完成脫鞋動作



4. 依次撕開兩條綁帶的魔術貼，從腳上拆下主機。

5. 取出感測器鞋墊，請小心操作，以免造成感測器線路損壞



6. 將（四塊）電極貼片取下，放置回塑膠片上。**此電極貼片可重複使用一星期**

注意：

設備每次充滿電，至少可完成三天的訓練時長。

為了防止設備電量不足而造成的訓練中斷，每次訓練結束拆卸設備後，請對設備進行充電。

一共训练二十天，一周训练五天，每天完成 45 分鐘到 90 分鐘的行路訓練，训练次數不限。

C-15: Developed Questionnaire

下肢居家復康訓練

您好，這是一份關於香港理工大學居家復康訓練的問卷調查。題目均無對錯之分，根據實際情況作答。您所提供的資訊只被用於研究，感謝您的支持和配合。

您的姓名 [填空題] *

_____

您的性別 [单选题] *

○男

○女

您的年齡 [填空題] *

_____

您的居住區 [填空題] *

_____

您的學歷 [单选题] *

○無正式學歷

○小學

○中學

○大專（high diploma）

○學士（bachelor）

○碩士及更高（master/PhD）

您現在是否在工作？[单选题] *

○是

○否

您的住房情況 [单选题] *

○租房

○公屋

○私樓

○政府宿舍

○其他 _____ *

您的手機使用能力 [单选题] *

○熟練（了解手機各項功能）

○夠用（可以完成訓練要求功能）

○缺乏（無法獨自完成訓練要求功能）

您的照顧者主要是 [单选题] *

○家人

○傭人

○無

○其他 _____ *

您的自我復康目標 [单选题] *

○完全正常 （可以跑步）

○基本正常（正常走路，出街）

○比之前有進步

○無所謂

請選擇最符合您想法的一項，1 代表完全不正確，7 代表完全正確[矩阵量表題] *

	1	2	3	4	5	6	7
該設備是有用的	○	○	○	○	○	○	○
我很快就學會使用該設備	○	○	○	○	○	○	○
該設備使用簡單	○	○	○	○	○	○	○
我覺得可以把該設備推薦給別人	○	○	○	○	○	○	○
該設備能幫助我完成訓練	○	○	○	○	○	○	○
該設備對用戶友好	○	○	○	○	○	○	○
我很快就熟練使用該設備	○	○	○	○	○	○	○
我對該設備很滿意	○	○	○	○	○	○	○

在本次下肢居家復康訓練中，我們提供了病友（及其家人）群組結伴訓練。

對於結伴訓練，請選擇最符合您想法的一項，1 代表完全不正確，7 代表完全正確[矩阵量表題] *

	1	2	3	4	5	6	7

交流訓練心得	○	○	○	○	○	○	○
獲得病友陪伴	○	○	○	○	○	○	○
病友互動愉快	○	○	○	○	○	○	○
訓練更有動力	○	○	○	○	○	○	○
訓練效果提升	○	○	○	○	○	○	○
訓練有競爭意識	○	○	○	○	○	○	○
治療師監督高效	○	○	○	○	○	○	○

請選擇最符合您想法的一項，1代表完全不正確，7代表完全正確。

在前三堂面對面訓練中：[矩阵量表题] *

	1	2	3	4	5	6	7
我認為這訓練很無聊	○	○	○	○	○	○	○
我覺得我很擅長這個訓練	○	○	○	○	○	○	○
我訓練時很努力	○	○	○	○	○	○	○
這訓練沒法吸引我的注意力	○	○	○	○	○	○	○
我在訓練中經常存在困難	○	○	○	○	○	○	○
我在做訓練時很緊張	○	○	○	○	○	○	○

我認為這個訓練能幫助我下肢復康	○	○	○	○	○	○	○
我沒有在訓練中投入大量精力	○	○	○	○	○	○	○
我認為這是一個重要的訓練	○	○	○	○	○	○	○
我希望能有更多的機會和治療師交流	○	○	○	○	○	○	○
我在做訓練時很放鬆	○	○	○	○	○	○	○
我覺得和治療師很疏遠	○	○	○	○	○	○	○
我能獲得治療師高效的監督	○	○	○	○	○	○	○
我的訓練成功率高	○	○	○	○	○	○	○
我覺得訓練環境很舒適	○	○	○	○	○	○	○
我覺得訓練環境能滿足我的需求	○	○	○	○	○	○	○
我能獲得治療師即時的反饋	○	○	○	○	○	○	○
我覺得復康效果很好	○	○	○	○	○	○	○
我覺得訓練總體舒適	○	○	○	○	○	○	○
我覺得該訓練能完成	○	○	○	○	○	○	○

我的復康目標							

請選擇最符合您想法的一項，1 代表完全不正確，7 代表完全正確。

在其後居家訓練中：[矩阵量表题] *

	1	2	3	4	5	6	7
這訓練沒法吸引我的注意力	○	○	○	○	○	○	○
我沒有在訓練中投入大量精力	○	○	○	○	○	○	○
我認為這訓練很無聊	○	○	○	○	○	○	○
我在訓練中經常存在困難	○	○	○	○	○	○	○
我覺得我很擅長這個訓練	○	○	○	○	○	○	○
我訓練時很努力	○	○	○	○	○	○	○
我在做訓練時很緊張	○	○	○	○	○	○	○
我認為這個訓練能幫助我下肢復康	○	○	○	○	○	○	○
我認為這是一個重要的訓練	○	○	○	○	○	○	○
我覺得和治療師很疏遠	○	○	○	○	○	○	○
我希望能有更多的機	○	○	○	○	○	○	○

會和治療師交流							
我在做訓練時很放鬆	○	○	○	○	○	○	○
我能獲得治療師高效的監督	○	○	○	○	○	○	○
我能獲得治療師即時的回饋	○	○	○	○	○	○	○
我覺得訓練環境很舒適	○	○	○	○	○	○	○
我覺得訓練環境能滿足我的需求	○	○	○	○	○	○	○
我的訓練成功率高	○	○	○	○	○	○	○
我覺得復康效果很好	○	○	○	○	○	○	○
我覺得訓練總體舒適	○	○	○	○	○	○	○
我覺得該訓練能完成我的復康目標	○	○	○	○	○	○	○

對本次居家訓練有什麼建議？ [填空題]

_____

Appendices D: Research Materials for Chapters 3 & 4

D-16: Consent Form for Chapters 3 & 4

參與研究知情同意書

研究題目： 使用上肢外掛系統對改善中風康復者在居家訓練的療效

同意聲明:

本人茲同意參與這項研究。

本人已閱讀以上有關此研究之資料，研究人員已向本人詳細解釋研究的細節。本人明白所有有關本研究的好處及風險。本人有機會向研究人員提出疑問，而研究人員亦已完滿地解答本人的疑問。對於此研究，本人已獲得足夠的資料。本人願意參與此項研究。

若本人因參與本研究而引致任何身體損傷，研究負責人將會為本人進行治療或轉介接受治療。本人不會透過簽署本同意書而放棄任何法律權利。

本人謹於本同意書簽署，証明本人提供的所有資料均為正確無誤。本人明白，本人可不提出任何原因而於任何時間退出本研究，同時不影響本人現在及日後所獲得的醫療及護理服務。

本人明白，本人之身分將獲得保密處理。本人亦允許臨床研究倫理委員會及有關法定機構在合適的條例及法例容許下及在不侵犯本人的私隱情況中，直接翻查本人的病歷記錄以核實臨床研究計劃之程式和/或數據。

若本人要求退出本研究，本人 □同意 /□ 不同意研究人員可以繼續使用本人退出本研究前所提供的研究數據。

參加者姓名（正楷）: 日期:	簽署(參加者):
研究員姓名（正楷）: 日期:	簽署(研究員):

Version 1 dated 13_August 2020

賠償和治療:

若您因參與本研究而引致任何身體損傷，研究負責人將會為您進行治療或轉介您接受治療。您不會透過簽署本同意書而放棄任何法律權利。

新資料:

如果有任何關於此研究並有可能會影響您是否繼續參與此研究之新資料，您將會收到相關的通知。

個人資料保密:

您的身份將會絕對保密。所有需要發表的資料或報導，將不會顯示您的身份。您所簽署的同意書會與您的個人資料分開保存，以進一步保護您的私隱，並只有本研究的研究人員可以翻閱。所有個人資料將會存放在只有研究人員可以接觸的電腦內，所得資料可以因應您的要求而抽出和銷毀，所有資料亦會在研究完成後三年銷毀。

依香港法律規定特別是第 486 章《個人資料（私隱）條例》)，您享有或可享有確保您的個人資料保密的權利，例如在或為本研究中有關收集、監管、保留、管理、控制、使用（包括分析或比較）、轉進或轉出香港、不披露、清除和／或以任何方式處理或棄置的權利。如有任何問題，請您諮詢個人資料私隱專員或其職員(電話號碼：2827 2827)，以瞭解妥善監控或監管您的個人資料保護之事宜，以確保您完整掌握和瞭解遵守規管個人資料私隱的法律之重要性。

參加者須知事項:

您和您的家人將獲得一份本研究的參與研究資料及已簽署的參與研究知情同意書副本。通過簽訂書面知情同意書，您授權九龍中及九龍東聯網臨床研究倫理委員會可直接核查您的研究數據。

聯絡方法:

如對是項研究有任何問題，可致電 24624228 聯絡主研究員沈文鶴先生。若您對作為研究參加者所享有的權利有任何疑問，請致電 3506 8888 與九龍中及九龍東聯網臨床研究倫理委員會聯絡。

D-17: Information Sheet for Chapters 3 & 4

參與研究資料頁

研究機構: 醫院管理局社區復康中心

研究題目: 使用上肢外骨骼系統對改善中風康復者在居家訓練的療效

首席研究員: 香港理工大學生物醫學工程學系助理教授胡曉翎博士

駐院研究員: 醫院管理局社區復康中心中心一級職業治療師沈文鶴先生

副研究員: 醫院管理局社區復康中心高級職業治療師陳家樑先生

醫院管理局黃大仙醫院職業治療部署理高級職業治療師陳金鳳小姐

研究目的: 這項研究的主要目的是探索可於家居使用的上肢外掛系統能否改善中風康復者的上肢功能及其持續效果

研究簡介: 大約七至八成中風康復者會有上肢功能缺失，持久及恒常的復康訓練有助提昇患者的上肢功能，但因為各種因素，包括疫情、時間及人手資源安排，患者往往不能長期接受持久及恒常的訓練。正因如此，一套可自行在家中進行上肢訓練的裝置有助解決以上問題。於是本中心連同香港理工大學合作應用大學所研發的一套輕巧可攜式外掛裝置，讓中風康復者可以在家居自行使用，因此您被邀請參與此次針對中風康復者訓練計劃的研究。本研究將會在醫管局社區復康中心招募二十名中風康復者及符合納入標準的病患者參與。在進行研究之前，研究員會向您解釋研究的程序。在您還沒有決定是否參與之前，請務必瞭解研究的目的及研究將涉及什麼。這份資料書詳述有關資訊，請仔細閱讀以下資料。如有必要，請您和您的家人、朋友及您的家庭醫生討論。若您有任何疑問，或想知道更多的資料，請向負責這項研究的人員詢問，然後周詳考慮並決定是否參與。

研究程序: 本研究將有二十名中風康復者參與。您的個人資料包括年齡、性別、教育程度、發病時間將會被記錄作研究之用。您會先接受本中心職業治療師在兩星期內進行三次評估（當中有兩次是常規評估以外的）：評估內容包括中風上肢的感官和肌肉功能；拿取不同形狀、大小和重量的物件以及中風上肢的肌肉張力狀況。完成並通過評估篩查的您會繼續參加研究。首先您需要使用此裝置於中心內進行訓練，訓練課程共三堂，每堂約兩個小時，訓練內容包括使用此裝置前的準備，例如裝置的使用和運作、學習配戴裝置、如何貼上電極片和家居訓練程序等。過程中您需要觀看四段示範影片，總片長少於六分鐘，完成後您可按需要獲得這些影片的網上連結或影碟一隻，供家中溫習程序使用。治療師並會進行家訪以提供家居訓練環境的建議。完成準備訓練後，研究員會借出一套裝置拿給您在家訓練，然後在家中每星期用三至五堂，每堂不多於兩小時，研究

員會定期檢測您訓練的進度並作出建議。在完成十七堂後，便可交還裝置。在完成整個訓練後，治療師會為您再進行以上提及的各樣評估，藉此了解此裝置對您的療效。在三個月及六個月後會再有兩次跟進評估以量度此訓練的持久成效。

預期研究的持續時間

您若按照職業治療師所建議的時間作家居訓練(每週三至五節)，總數共十七次訓練，每次約需兩小時。並會於研究開始和結束作評估，預期整個過程於四至七星期內成完成。並在完成結束評估三個月及六個月後，本中心職業治療師會再聯絡您進行跟進評估以量度此訓練的持久成效。

其他程序或治療

假若您決定不參與研究，您可以繼續接受原先所安排的恒常治療。

預期的好處:

透過治療預期會提升您的上肢活動能力，從而改善您的手部功能及日常生活技巧。

預期風險:

此裝置屬於創新的治療及訓練器材並處於研究階段，即使此裝置對您治療有成效，在完成家居訓練後您仍需交還給中心，而不能繼續使用。除此以外，參與此研究及使用此裝置並沒有風險。

自願參與 / 中途退出:

所有參與屬於自願性質，您有權於任何時候退出參與研究，這將不會影響您現在或將來的正常醫療護理服務。一旦您要退出研究，如果沒有得到您的同意，退出前所收集的數據將會被銷毀。您亦可於知情同意書表示允許研究人員在您退出後繼續使用從您身上所收集的數據用於本研究用途。您會給予足夠的時間去考慮是否參與這項研究。您簽署參與研究知情同意書後，會獲得一份已簽署的同意書副本作為紀錄。即使您已簽署同意書，也可以在任何時候改變參與這項研究的意願。

參與研究收費及報酬:

除要繳付常規醫療費用外，參與此項研究並無額外收費及報酬，亦不會影響您任何現有及日後提供的治療。如在正常使用過程中，裝置及/或配件受到任何損壞或遺失，請您立即致電 24624228 通知沈文鶴先生，並安排作出更換和維修，您不用承擔有關賠償。在研究完成後，您需要把治療裝置退還。

D-18: Developed Questionnaire

實驗室回訪問卷

您好，這是一份關於香港理工大學遠程復康訓練的問卷調查。題目均無對錯之分，根據實際情況作答即可。你所提供的資訊將只被用於研究，不會外泄，感謝你的支持和配合。

您的名字 [填空题] *

_____

您的年齡 [填空题] *

_____

您的性別 [单选题] *

○男

○女

您中風的年份 [填空题] *

_____

您是什麼中風類型 [单选题] *

○缺血型（腦血管阻塞）

○出血型（腦血管爆裂）

○不确定

請選擇最符合你想法的一項，1代表完全不正確，7代表完全正確[矩阵单选题] *

	1	2	3	4	5	6	7
該設備使訓練更有效	○	○	○	○	○	○	○
該設備是有用的	○	○	○	○	○	○	○

該設備讓我對我的治療有更多的控制權	○	○	○	○	○	○	○
需要最少的步驟完成我想做的	○	○	○	○	○	○	○
該設備使用靈活	○	○	○	○	○	○	○
我不用書面說明就能使用該設備	○	○	○	○	○	○	○
使用該設備的時候如常運作	○	○	○	○	○	○	○
臨時和長期用戶都會喜歡該設備	○	○	○	○	○	○	○
我覺得可以把這個設備推薦給別人	○	○	○	○	○	○	○
該設備太棒了	○	○	○	○	○	○	○

請選擇最符合你想法的一項，1代表完全不正確，7代表完全正確[矩阵量表题] *

	1	2	3	4	5	6	7
該設備使用容易	○	○	○	○	○	○	○
該設備使用簡單	○	○	○	○	○	○	○
該設備對用戶友好	○	○	○	○	○	○	○
該設備使用起來毫不費力	○	○	○	○	○	○	○

我每次都能成功地使用該設備	○	○	○	○	○	○	○
很容易學會使用這套設備	○	○	○	○	○	○	○
我很快就熟練使用該設備	○	○	○	○	○	○	○
該設備用起來很有趣	○	○	○	○	○	○	○
我覺得我需要該設備	○	○	○	○	○	○	○
該設備使用起來很愉快	○	○	○	○	○	○	○

請選擇最符合你想法的一項，1代表完全不正確，7代表完全正確[矩阵量表题] *

	1	2	3	4	5	6	7
該設備使訓練更高效	○	○	○	○	○	○	○
該設備使我想要完成的事情更容易完成	○	○	○	○	○	○	○
該設備節省了我的時間	○	○	○	○	○	○	○
該設備滿足了我的需要	○	○	○	○	○	○	○
該設備能幫助我完成訓練	○	○	○	○	○	○	○

我能從使用錯誤中很快恢復	○	○	○	○	○	○	○
我很快就學會了使用該設備	○	○	○	○	○	○	○
我很容易記住如何使用該設備	○	○	○	○	○	○	○
我對這套設備很滿意	○	○	○	○	○	○	○
該設備是我想要的	○	○	○	○	○	○	○

請選擇最符合你想法的一項，1代表完全不正確，7代表完全正確[矩阵量表题] *

	1	2	3	4	5	6	7
我在做訓練時很放鬆	○	○	○	○	○	○	○
我希望能有更多的機會和幫忙訓練的工作人員交流	○	○	○	○	○	○	○
我參加這個訓練是因為我別無選擇	○	○	○	○	○	○	○
我很享受這個訓練過程	○	○	○	○	○	○	○
我對自己在這項訓練中的表現很滿意	○	○	○	○	○	○	○
我覺得做這個訓練不	○	○	○	○	○	○	○

是我自己的選擇							
如果我們經常交流，幫忙訓練的工作人員很可能和我成為朋友	○	○	○	○	○	○	○
我願意再參加一次訓練，因為這對我有價值	○	○	○	○	○	○	○
我覺得和幫忙訓練的工作人員很疏遠	○	○	○	○	○	○	○
我訓練時很努力	○	○	○	○	○	○	○

請選擇最符合你想法的一項，1代表完全不正確，7代表完全正確[矩阵量表题] *

	1	2	3	4	5	6	7
我覺得我必須參加這個訓練	○	○	○	○	○	○	○
我相信這次訓練對我有一定的價值	○	○	○	○	○	○	○
這訓練沒法吸引我的注意力	○	○	○	○	○	○	○
在訓練中，我沒有很努力地做好	○	○	○	○	○	○	○
我在做訓練時是有壓	○	○	○	○	○	○	○

力的							
我認為這個訓練很有趣	○	○	○	○	○	○	○
這是一個我不能完成得很好的訓練	○	○	○	○	○	○	○
我認為這訓練很無聊	○	○	○	○	○	○	○
我覺得我真的可以信任幫忙訓練的工作人員	○	○	○	○	○	○	○
我沒有在訓練中投入大量精力	○	○	○	○	○	○	○

請選擇最符合你想法的一項，1代表完全不正確，7代表完全正確[矩阵量表题] *

	1	2	3	4	5	6	7
我在做訓練時很緊張	○	○	○	○	○	○	○
我參加這個訓練是因為我想參加	○	○	○	○	○	○	○
做好訓練對我來說非常重要	○	○	○	○	○	○	○
我對這個訓練很在行	○	○	○	○	○	○	○
我認為參加這個訓練可以幫助我上肢康復	○	○	○	○	○	○	○

我覺得我很擅長這個訓練	○	○	○	○	○	○	○
我在做訓練時是焦慮的	○	○	○	○	○	○	○
我認為這是一個重要的訓練	○	○	○	○	○	○	○

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