APPLICATION OF WEARABLE TECHNOLOGY IN UPPER LIMB STROKE REHABILITATION IN THE HOME SETTING

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PhD

The Hong Kong Polytechnic University

2024

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A thesis submitted in Partial fulfilment of the requirements for the degree of Doctor of Philosophy

May 2024

Certificate of originality

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Toh Fong Mei (Name of student)

ABSTRACT

Stroke is a leading cause of disability, significantly affecting surivivors' quality of life. Research indicates that over 20 hours of task specific training per month is essential for optimal UL recovery post-stroke. Self-directed UL rehabilitation at home provides a viable option for intensive practice especially given the constrained health services. Wearable technology, which provides augmented feedback and enables remote monitoring, holds promise for home-based UL rehabilitation. However, its effectiveness in rehabilitating the hemiparetic UL in home settings remains unclear.

This thesis introduces a new telerehabilitation approach using the "Smart Reminder" (SR) wearable device, an evolution of the "Remind to move" device specifically designed for home-based training for stroke individuals, with two additional features. The SR device includes a gyroscope to track the range of motion of the hemiparetic arm and integrates with a smartphone application. The thesis aims to generate knowledge and evidence on the effects of telerehabilitation using the SR device for home-based self-directed UL training in stroke survivors.

Five studies were conducted to achieve the thesis's aims. Two literature reviews (Studies 1 and 2) laided the theoretical groundwork. Study 1 (Chapter 2) is a systematic review and meta-analysis that found home-based UL interventions more effective than clinic-based therapies and identified critical factors for implementing technology-based interventions at home. Study 2 (Chapter 3) is a scoping review that identified three key considerations for designing wearable devices: using a smartphone as a visual display, implementing a fading feedback schedule, and ensuring an interactive interface.

Building on these reviews, three empirical studies (Studies 3, 4, and 5) were conducted. Study 3 (Chapter 4), a mixed-methods usability study, evaluated user perspectives and factors influencing the use of the SR device. The study confirmed the device's usability [system usability scale: 84.3 (12.3)] and demonstrated a high therapy adherence rate (91%) among local stroke survivors. Qualitative results from Study 3 identified four primary considerations for wearable-based intervention: wearability, user interface, system performance, and exercise content, which were applied in Study 5.

Two clinical trials (Studies 4 and 5) investigated the clinical effects of SR in improving the hemiplegic UL outcomes of the stroke survivors. Study 4 (Chapter 5 in the thesis), a feasibility pilot randomized crossover trial (n=12), suggested that a 4-week telerehabilitation program using the SR improved the hemiplegic UL function and demonstrated its feasibility for home use. Study 5 (Chapter 6 in the thesis), a randomized controlled trial (n=40), compared the telerehabilitation training using the SR device with conventional training using a sham device. The SR group showed significant improvements in Fugl Meyer Assessment-Upper Extremity (FMA-UE) scores ($p=0.036$) and higher adherence rates (97% vs. 82.3%, $p=0.038$). Subgroup analysis revealed that participants with severe paresis experienced a notable improvement with SR intervention, in the FMA-UE scores (mean difference: 3.38, $p=0.008$) compared to the sham group.

In summary, this thesis advances the understanding of the wearable technology in stroke rehabilitation and confirmed the efficacy of the telerehabilitation using SR wearable in improving the motor outcomes of the hemiplegic UL in persons with stroke. (499 words)

LIST OF RESEARCH OUTPUT DURING THIS CANDIDATURE

A. Journal publications during the PhD study period (arising from this thesis)

1. **Toh, S. F. M.,** Chia, P. F., & Fong, K. N. K. (2022). Effectiveness of home-based upper limb rehabilitation in stroke survivors: A systematic review and meta-analysis. *Frontiers in Neurology*, 13, 964196. https://doi.org/10.3389/fneur.2022.964196

2. **Toh, S. F. M.,** Gonzalez, P. C., & Fong, K. N. K. (2023). Usability of a wearable device for home-based upper limb telerehabilitation in persons with stroke: A mixed-methods study. *Digital Health*, 9, 20552076231153737. https://doi.org/10.1177/20552076231153737

3. **Toh, S. F. M.,** Fong, K. N. K., Gonzalez, P. C., & Tang, Y. M. (2023). Application of home-based wearable technologies in physical rehabilitation for stroke: A scoping review. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 10.1109/TNSRE.2023.3252880. https://doi.org/10.1109/TNSRE.2023.3252880

4. **Toh, F. M.,** Lam, W. W., Gonzalez, P. C., & Fong, K. N. (2024). 'Smart reminder': A feasibility pilot study on the effects of a wearable device treatment on the hemiplegic

upper limb in persons with stroke. *Journal of Telemedicine and Telecare,* 1357633X231222297. https://doi.org/10.1177/1357633X231222297

5. **Toh, F. M.,** Lam, W. W., Gonzalez, P. C., & Fong, K. N. (under revision). 'Smart reminder': A Randomized Controlled Trial on the effects of a wearable- based intervention on the hemiparetic upper limb in persons with stroke. *Neurorehabilitation and Neural Repair*.

B. Conference presentations during PhD study period (arising from thesis)

1. **Toh, S.F.M.** (2021). *Effectiveness of Home-Based Upper Limb Rehabilitation in Stroke Survivors: A Systematic Review and Meta-Analysis*. The 12th Pan-Pacific Conference on Rehabilitation from 27th to 28th November 2021. Hong Kong SAR, China. [Oral Presentation]

2. **Toh, S.F.M.** (2023). *Effects of telerehabilitation using "Smart Reminder" on hemiplegic upper limb recovery in stroke survivors*. Rehab Week 2023 from 24th to 28th September 2023. Singapore. [Poster Presentation]

3. **Toh, S.F.M.** (2023). *Effects of telerehabilitation using "Smart Reminder" on hemiplegic upper limb recovery in stroke survivors*. The 30th Annual Congress of Gerontology. on 18th November 2023. Hong Kong SAR, China. [Oral Presentation]

Journal publications during PhD study period (not arising from this thesis)

1. Leong, S. C., Tang, Y. M., Toh, F. M., & Fong, K. N. K. (2022). Examining the effectiveness of virtual, augmented, and mixed reality (VAMR) therapy for upper limb recovery and activities of daily living in stroke patients: a systematic review and meta-analysis. *Journal of NeuroEngineering and Rehabilitation.* https://doi.org/10.1186/s12984-022-01071-x

C. Award to the student during the PhD study period (arising from this thesis)

1. 1st Runner-up, *Faculty of Health and Social Sciences 3 MT competition 2023*, The Hong Kong Polytechnic University, Hong Kong SAR, 15 June 2023.

ACKNOWLEDGEMENTS

The progress of the current PhD research has been guided and supported by many individuals whose names have not all been mentioned. Their contributions are sincerely appreciated. Firstly, I would like to express my utmost gratitude to the Almighty God for the wisdom and perseverance bestowed on me to sustain this research journey so far as I struggled with my commitments. Furthermore, I would like to thank and express my deepest and sincere gratitude to my Chief supervisor, Professor Kenneth Fong, for his guidance and support through the phases of the PhD research journey.

Also, I would like to thank my fellow and previous lab mates, Winnie Lam, Dr Pablo Cruz Gonzalez, and Dr Jacky Zhang, for their unswerving support in helping and guiding me in conducting the research trials for this PhD thesis. In addition, my sincere appreciation goes to the study participants and co-authors for their contributions to the research studies. I would also like to thank Mr Newman Ho and his team from Zunosaki Co. Ltd for their technical support in the development and modification of "Smart Reminder" device.

Lastly, I want to extend my gratitude to my husband, Peter, for his unconditional love and tremendous support in my whole PhD journey, sacrificing his career progression to relocate with me and to take care of me and my two boys, Luke and Jonathan. Without his support, I would not have gone so far in this PhD journey. I will cherish every bit of knowledge and skills acquired throughout this academic pursuit.

Table of Contents

List of Figures

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Chapter 7

List of Tables

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

LIST OF ABBREVIATIONS

ADL: Activity of Daily Living

App: Application

ANCOVA: Analysis of Covariance

ARAT: Action Research Arm Test

BBT: Box and Block Test

BI: Bartel Index

CIMT: Constraint-Induced Movement Therapy

CNS: Central Nervous System

CONSORT: Consolidated Standards of Reporting Trials

COREQ: Consolidated Criteria for Reporting Qualitative Research

EMG: Electromyography

FMA-UE: Fugl Meyer Assessment- Upper Extremity

FIM: Functional Independence Measure

FTHUE-HK: Functional Test of Hemiplegic Upper Extremity-Hong Kong Version

GDP: Gross Domestic Product

JTT: Jebsen Taylor Test

ICT: Information and Communication Technology

IQR: Interquartile Range

KP: Knowledge of Performance

KR: Knowledge of Result

LOCF: Last Observation Carried Forward

LL: Lower Limb

mCIMT: Modified Constraint-Induced Movement Therapy

MAL-AOU: Motor Activity Log-Amount of Use

MAL-QOM: Motor Activity Log- Quality of Movement

MCP: Metacarpophalangeal

MD: Mean Difference

MT: Mirror Therapy

NDT: Neurodevelopmental Treatment

NIH: National Institute of Health

NMES: Neuromuscular Electrical Stimulation

PCC: Population Concept Context

Pedro: Physiotherapy Evidence Database

PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses

RCT: Randomized Controlled Trial

ROM: Range of Motion

rTMS: Repetitive Transcranial Magnetic Stimulation

SD: Standard deviation

SMD: Standardized Mean Difference

SR: ‘Smart Reminder’

SUS: System Usability Scale

TR: Telerehabilitation

TMS: Transcranial Magnetic Stimulation

tDCs: Transcranial Direct Current stimulation

UL: Upper Limb

UTAUT: Unified Theory of Acceptance and Use of Technology

VR: Virtual Reality

WMFT: Wolf Motor Function Test

WSR: Wearable Soft Robotic

9-HPT: Nine-Hole Peg Test

Chapter 1: Introduction

This chapter provides the extant background knowledge related to the work conducted by the author of the thesis. Some of the material in this chapter was used in the author's submission of confirmation of registration as a full-time PhD candidate in the Department of Rehabilitation Sciences in September 2022.

1.1 Chapter overview

This chapter briefly introduces stroke and its related hemiplegic upper limb (UL) impairments and reviews the current evidence for UL rehabilitation interventions after stroke. Due to the ongoing constraints of healthcare resources, the healthcare field's emphasis has increasingly been placed on shifting rehabilitation to be more self-directed and conducted in the home setting instead of the hospital or clinic. This chapter explains the rationale for home-based UL rehabilitation, discusses the mechanisms for applying wearable technology in stroke rehabilitation, and describes the technology's theoretical framework. After the research gaps and the rationale for this area of investigation have been explained, the outline of the thesis is presented.

1.2 General introduction to stroke

Stroke is a complex and disabling condition that affects a person's long-term quality of life. It is characterized as a neurological deficit that occurs when there is an acute focal injury to the brain due to a vascular cause that disrupts the supply of adequate oxygen in the brain, leading to ischemic damage and death of the brain cells (Gillen & Nilsen, 2020; Krakauer, 2006; Sacco et al., 2013). Globally, stroke is the second-largest cause of death and the main cause of adult disability (Feigin, 2007; Katan & Luft, 2018; Strong et al., 2007). As one of the world's most populous countries, China faces significant health problems due to stroke, and stroke is the leading cause of death (Li et al., 2019; Vos et al., 2020; Wu et al., 2019). Hong Kong also has experienced a significant burden from stroke, with a crude death rate of 42.1 per 100,000 population in 2021 (Hong Kong SAR Census and Statistics Department, 2021). Annually, approximately 25,000 people in Hong Kong suffer a stroke, which is 0.8% of its population (Hong Kong SAR Census and Statistics Department, 2021). In Singapore, the crude incidence rate of stroke significantly increased over the recent decade of 2010 to 2020, from 188.9 to

256.0 per 100,000 population (National Registry of Diseases Office, 2022). Compared with Western countries such as Europe, the United States, and Australia, the average mortality rate due to stroke is higher in Asia (Abduboriyevna & Yusufjonovich, 2018). Feigin et al. (2014) projected that the global burden of stroke resulting from medical complications, disability, and mortality will double within the next 15 years.

Apart from mortality, stroke causes substantial economic burdens, which vary among Asian countries (Evers et al., 2004). Specifically, recent research has shown that the costs of stroke management vary across three Southeast Asian countries (i.e., Indonesia, Malaysia, and Singapore) (Wijaya et al., 2019). According to those researchers, in Indonesia, the cost of stroke was $135.55 per day care (3.88% of GDP per capita), while it was $227.53 (2.11% of GDP per capita) in Malaysia and $366.76 per day care (0.65% of GDP per capita) in Singapore (Wijaya et al., 2019). In Hong Kong, the cost of stroke care (hospitalization, outpatient care, and allied health services) is projected to be HK$3,979 million annually by 2036 (Yu et al., 2012). Given such considerable economic burdens, greater attention must be paid to evidence-based stroke pathways and effective planning for stroke services (Turana et al., 2021). In addition, stroke prevention and effective rehabilitation play a pivotal role in reducing unnecessary stroke expenditures and stroke-related disabilities.

1.3 Upper limb impairments and motor learning after stroke

The most significant impairment caused by stroke is motor impairment, which refers to a loss or limitation of muscle control and function or movement or mobility (Wade, 1992). Langhorne et al. (2009) highlighted that 80% of stroke survivors face motor impairment affecting one side of their body. These impairments cause disabilities in activities of daily living (ADLs) and reduce the individual's quality of life (Nichols-Larsen et al., 2005). Research has

suggested that only 15% of stroke survivors will recover complete function for both upper and lower limbs (Hendricks et al., 2002). Upper limb hemiparesis is considered to be a significant contributor to disabilities and loss of independence after stroke (Faria-Fortini et al., 2011).

Common manifestations of UL impairments are muscle weakness, changes in muscle tone, laxity of joints, diminished sensation, and impaired motor control (Hatem et al., 2016), and they are responsible for the functional limitations affecting the use of the hemiplegic UL after stroke (Raghavan, 2015). However, understanding UL impairment is complex because the impairments constantly evolve. For instance, the type and nature of UL impairments change as motor recovery progresses, and multiple impairments can happen at the same time and (Raghavan, 2015). Raghavan (2015) proposed three main functional consequences of stroke with the hemiplegic UL: (a) learned nonuse, (b) learned bad use, and (c) forgetting. In the following sections, the motor learning theories will be discussed along with these functional consequences of the hemiplegic UL as proposed by Raghavan (2015).

1.3.1 Motor Learning theories

According to Fitts and Posner (1967), there are three stages of motor skill acquisition: the cognitive, associative, and autonomous stages. The cognitive stage marks the initial period when task goals are determined and used to determine the necessary sequence of actions (Fitts & Posner, 1967). The use of explicit knowledge is needed for learning in this stage (Taylor & Ivry, 2012). During the associative stage, individuals concentrate on the precise details of the action sequence and its transitions, leading to improved skill proficiency (Fitts & Posner, 1967; Taylor & Ivry, 2012). Finally, in the autonomous stage, motor action is practised to hone performance in an automatized routine (Fitts & Posner, 1967; Taylor & Ivry, 2012).

Theories on both model-based and model-free learning have been used to explain the mechanism of motor learning (Richardson et al., 2013). Model-based learning is defined by Haith and Krakauer (2013, p. 3) as " the use of experience to build models of the dynamics of the motor apparatus and environment and structure of task to compute the value function based on these models". Model-free learning, on the other hand, also known as reinforcement learning, is " to learn the value function based on a process of trial and error- to explore the space of potential actions in each state and keep track of which states and actions lead, either directly or indirectly to successful outcomes" (Haith & Krakauer, 2013, p.3).

Using both the theories of model-based learning and that of model-free learning, V.S. Huang et al. (2011) proposed that three independent processes occur over several time scales in motor skills learning. Firstly, "sensorimotor mappings develop through a trial-and-error process which involving adapting the motor practice of a task using appropriate error detection" (Raghavan, 2015, p.6). Motor adaptation is a quick learning process (Joiner & Smith, 2008) in which individuals adjust their movement to meet the task demands through trial and error (Bastian, 2008). The second process is repetition, which involves performing a newly adapted movement multiple times gradually adjusting directional biases towards the repeated movement (Galea & Celnik, 2009). The third process is operant reinforcement of the adapted movement and reduced the errors successfully (V.S. Huang et al., 2011). V.S. Huang et al. (2011) indicated that this operant reinforcement leads to quicker relearning in future attempts. Additionally , they demonstrated that motor learning is most effective when the adaptation of acquired motor skills is repeated multiple times to ensure adequate sensorimotor mapping (V.S. Huang et al., 2011).

1.3.2 Nonuse and learned nonuse

Learned nonuse refers to the behaviors that stroke individuals exhibit when using their non-hemiplegic arm to perform tasks that the affected arm would typically have done before a stroke but may not be able to perform as easily after the stroke due to neurological conditions (X. Wei, 2018). Initially, individuals may not use their affected arm due to paralysis and sensory loss in the arm or to spatial and body neglect after a stroke (Raghavan, 2015). Over time, this 'nonuse' behavior becomes habitual and learned, leading to individuals with stroke avoid using their affected arm in their daily activities (Raghavan, 2015). This lack of engagement of the affected UL hinders its motor recovery as the re-learning of lost motor skills after a stroke requires a cognitive process involving the conscious thought and execution of the movement sequences (Fitts & Posner, 1967). When the affected UL is neglected, stroke individuals miss out on valuable opportunities to re-learn and reinforce these essential motor skills, affecting the functional performance of the affected limb.

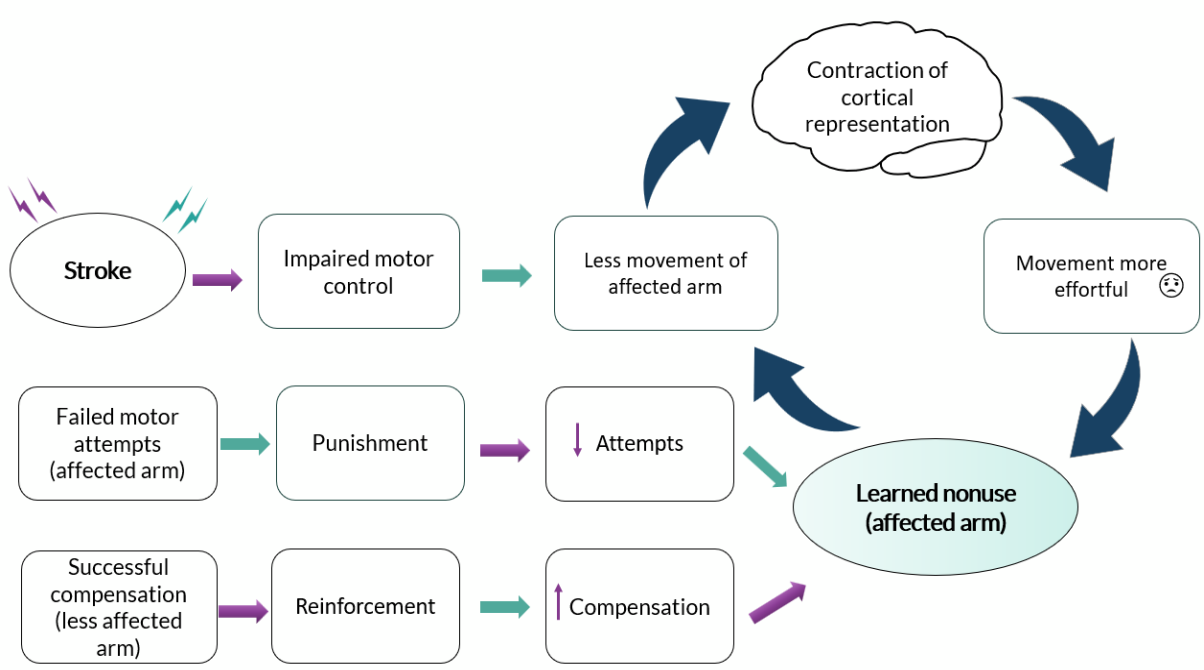
Edward Taub et al. (2002) described the development of learned nonuse behavior in three processes: a) physical damage to the central nervous system, which is caused by impaired motor control and contracted cortical representation due to reduced movement; b) experienced failure when using the affected UL that discourages its use; and c) a positive experience in using the unaffected UL further reinforces compensatory behavior. Figure 1-1 illustrates the model of the development of learned nonuse by Taub et al. (2002). Sunderland and Tuke (2005) expanded Taub's model and identified three levels of behaviors: basic control, functional ability, and spontaneous hand use, as shown in Figure 1-2. After a stroke, the lesioned motor cortex and contracted cortical representation cause impaired motor control, leading to poor functional ability and further inhibiting spontaneous use of the affected hand (Sunderland & Tuke, 2005).

1.3.3 Learned bad use

The concept of 'learned bad use,' as described by Raghavan (2015, p. 4), refers to the habitual reliance on compensatory movements by individuals with stroke when using their affected arm to perform tasks. This behavior often emerges as a response to motor and sensory impairments, abnormal motor synergies, and spasticity of the hemiparetic UL resulting from the stroke (McCrea et al., 2005; Raghavan, 2015). Over time, these compensatory strategies become ingrained, potentially limiting recovery and reinforcing maladaptive movement patterns (Raghavan, 2015). Using compensatory strategies with the hemiparetic arm for reaching and grasping activities is commonly observed in individuals with stroke (Levin et al., 2009). For instance, Cirstea and Levin (2000) highlighted that patients with stroke tend to flex their trunks rather than extend their elbows in reaching tasks. Another example is provided by García and colleagues (2017), who found that stroke individuals with more severe impairments used compensatory grasp strategies, such as the digital-palmar grasp or raking grasp (involving the use of the palm), compared to the standard grasps used by healthy individuals that primarily involve the distal pads of the fingers without engaging the proximal phalanx.

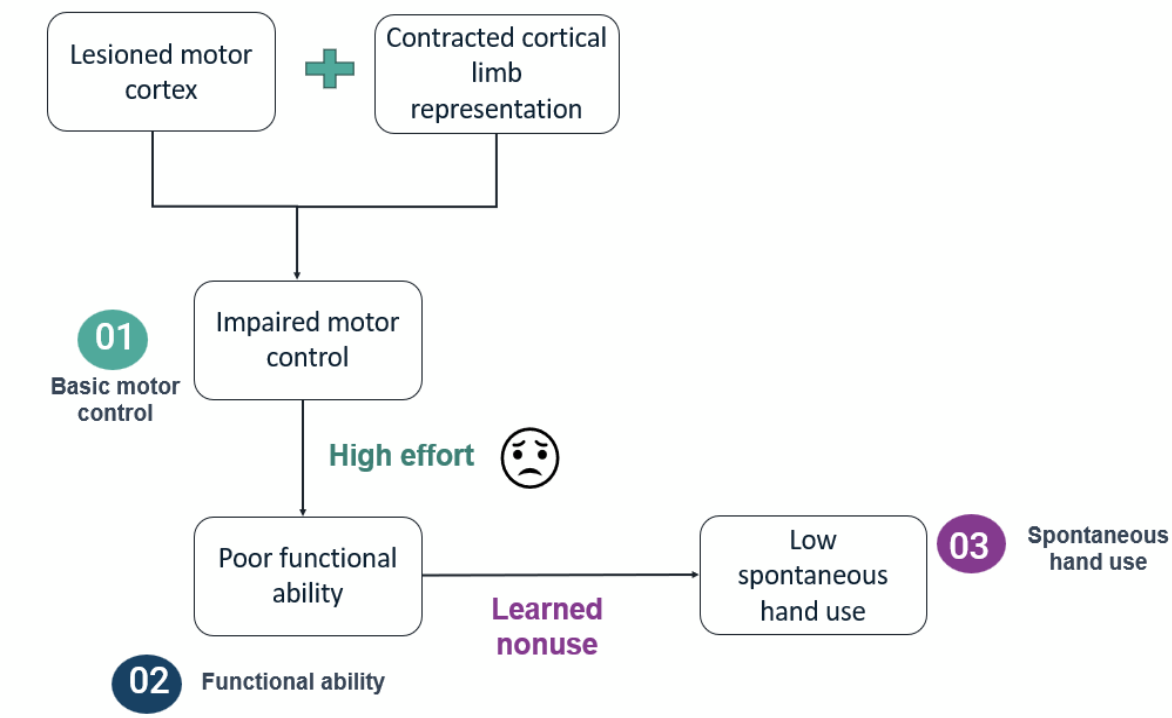
While stroke survivors may initially rely on compensatory movements to successfully complete a task, their lack of accuracy eventually reduces efficiency and increases the likelihood of failure (Raghavan, 2015). Repeatedly using the compensatory strategies leads to a decline in task performance and efficiency (Dickinson, 1985) resulting in what is termed "learned bad use" when these strategies remain uncorrected (Raghavan, 2015, p. 4). In the initial phase of motor skill acquisition, feedback is crucial for detecting errors and adapting the motor practice to ensure that stroke survivors use correct movement patterns and achieve proper sensorimotor mappings (Raghavan, 2015).

Figure 1-1: Model of Learned Nonuse



Note: Figure modified from Taub et al. (2002)

Figure 1- 2: Expanded Model of Learned Nonuse



Note: Figure modified from Sunderland et al. (2005)

Therefore, to counteract “learned bad use”, training should focus on minimizing the use of compensatory strategies (Raghavan, 2015). For example, trunk restraint is a strategy used to correct trunk flexion - a compensatory movement during reaching activities, encouraging patients to learn the proper movement of extending their elbows (Michaelsen et al., 2001).

1.3.4 Forgetting

The third functional consequence of UL impairment is forgetting, which refers to losing the ability to retain a motor skill (Schmidt et al., 2018). Generally, “once a motor skill is acquired, it is expected to be retained forever, despite the absence of interval training” (Raghavan, 2015, p. 5)(for example, writing or walking). However, the expectation of skill retention may not hold for individuals with stroke . Studies by Krakauer (2006) and Takahashi and Reinkensmeyer (2003) have suggested forgetting of the motor skills can occur in persons with stroke when there is a disruption in rehabilitation. Raghavan (2015, p. 5) described that “while newly acquired skills in healthy individuals tend to be relatively stable, these skills are more transient in persons with stroke”.

Individuals with stroke face several challenges in three motor skill learning processes described by V.S. Huang et al. (2011)-(a) sensorimotor mapping through trial and error motor adaptation, (b) repetition of newly adapted movement and (c) operant reinforcement of adapted movement with error reduction. According to Raghavan (2015, p. 6), “impaired sensorimotor adaptation and the lack of long-term practice opportunities in stroke individuals might lead to the unlearning and forgetting of motor skills (Kitago et al., 2013).” Therefore, Raghavan (2015) suggested that the first step to overcome “learned bad use” or forgetting is, to develop appropriate sensorimotor mappings, reinforce correct motor adaptations through repetition, thereby facilitating quicker relearning in future attempts.

1.4 Upper limb recovery after stroke

The nature of stroke recovery is heterogeneous, and a stroke's long-term effects are highly influenced by the site and initial lesion size and the extent of the subsequent recovery (Langhorne et al., 2011). Stroke recovery is considered a complex process involving spontaneous recovery, restitution (restoring the functions of the damaged neural tissues), substitution (reorganizing the spared neural pathway to learn lost functions) (Laurence & Stein, 1978) and compensation (achieving a goal by substituting with a new approach instead of using their usual pre-stroke behavioral repertoire) (Bernhardt et al., 2017; Kwakkel, Kollen, & Lindeman, 2004). The time elapsed after a stroke is generally divided into several phases. The Stroke Roundtable Consortium (2017) divides the phases of stroke into the hyperacute phase (the first 24 hours after stroke), the acute phase (initial 7 days after stroke), the early subacute phase (the first 3 months after stroke), the late subacute phase (the first 4 to 6months after stroke) and the chronic phase (from 6 months after the stroke onward).

Langhorne et al. (2011) proposed a hypothetical pattern of stroke recovery, as is presented in Figure 1-3. The proposed stroke recovery pattern suggests that improvement after a stroke is rapid in the initial and subacute stages due to spontaneous recovery, and the recovery process gradually slows down after three months (Langhorne et al., 2011). Upper limb function often recovers slowly and incompletely after a stroke (Ingwersen et al., 2021). In the chronic phase, Kwakkel and Kollen (2013) stated that 33% to 60% of stroke survivors had little or no function in their hemiplegic arm. After stroke, the rate of motor recovery differs significantly between the upper and lower limbs. One study found that 65% of patients with initial lower limb (LL) deficits improved their function (Hendricks et al., 2002), while the probability of recovery for the upper limb was below 15% (Cauraugh & Summers, 2005). Desrosiers et al. (2003) commented that UL recovery is more challenging than LL recovery, and the recovery is smaller in the initial period.

The challenge in hemiplegic UL recovery compares with that of the hemiplegic LL can be attributed to four main issues: 1) cortical involvement, 2) complexity of UL motor control, 3) compensation of movement (X. Wei, 2018) and 4) environmental feedback. First, the sensorimotor and neural networks involved in the upper limbs have a broader and more complex cortical representation than those in the lower limbs do (X. Wei, 2018), with more brain regions being involved when the UL moves (Scarabino & Salvolini, 2006).

Second, ULs perform more complex functions than LLs do, and they have more intrinsic muscles (X. Wei, 2018). In contrast to LL reflexes, which are monosynaptic, UL reflexes are polysynaptic (Latash, 2008). Third, individuals with stroke tend to compensate for the hemiplegic arm by using the less affected arm to perform daily tasks (Taub et al., 1994), whereas with a hemiplegic leg, once they try to stand and walk, they are forced to use the hemiplegic leg and the uncompromised leg. Last, a hemiplegic leg has another advantage over a hemiplegic arm in that weight bearing on the hemiplegic LL occurs once a person with stroke steps onto the floor, and the floor gives tactile feedback (through environments such as the floor and footwear). Furthermore, individuals with hemiplegic lower limbs can use a walking aid or assistive device (environmental object) for assistance.

Figure 1-4 is a graph comparing the recovery rate after strokes from a study by K. B. Lee et al. (2015). As with the case of the hypothetical recovery pattern of stroke by Langhorne and colleagues (2009), the graph in Figure 1-4 reveals that the most significant degree of recovery happened in the first month after treatment for a stroke, followed by a more gradual recovery rate over the period from 3 to 6 months after stroke (K.B. Lee et al., 2015). In addition, the graph shows a considerable difference between the motor function of the upper and lower limbs, with the UL motor function having a relatively lower score than the LL did (K.B. Lee et al., 2015). One possible reason for the difference can be that the UL contributes much less than the LL did in the recovery period, so the recovery interval is prolonged (Desrosiers et al., 2003).

Figure 1-3: Hypothetical Stroke Recovery Pattern Proposed by Langhorne et al. (2011)

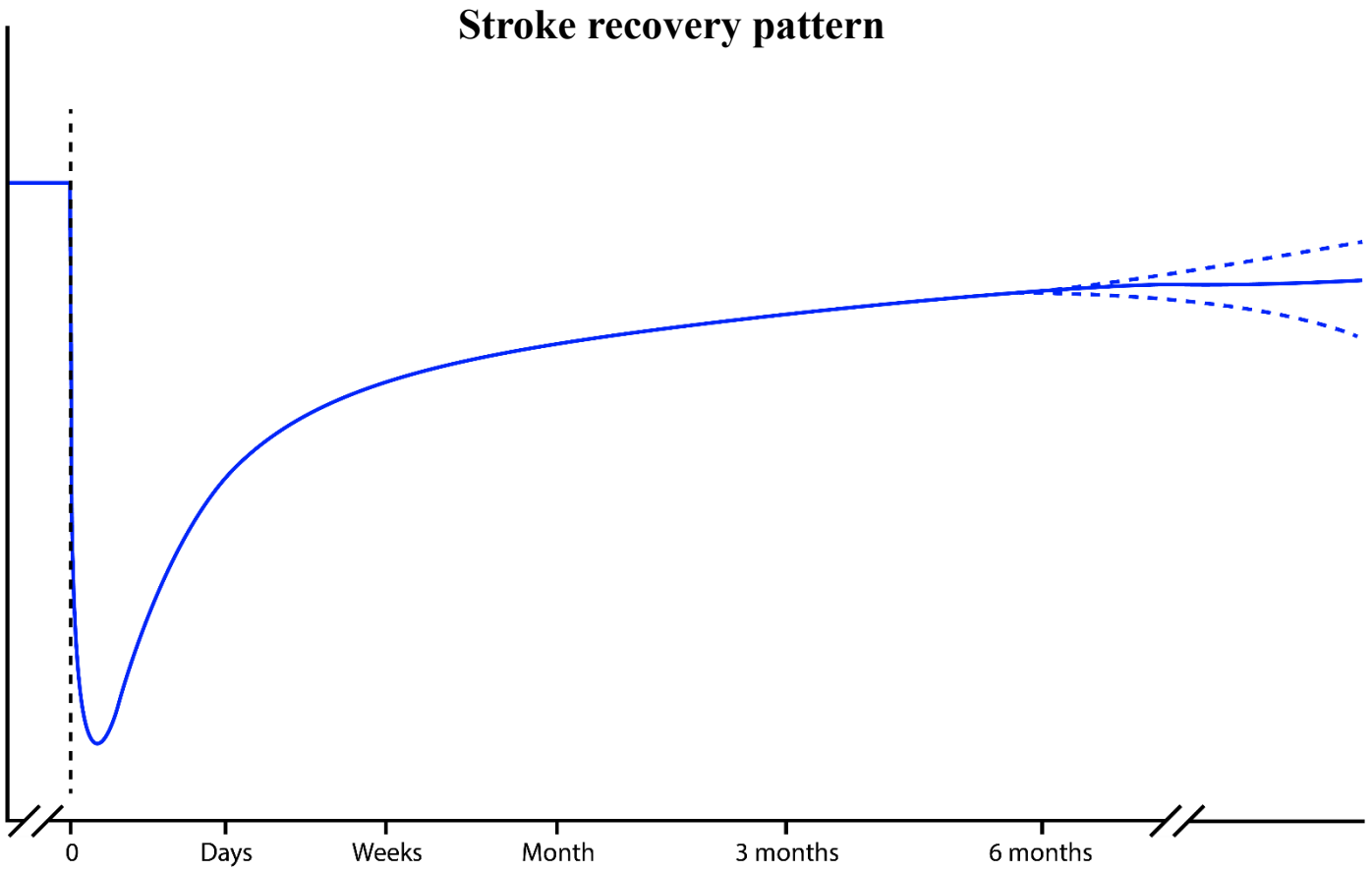
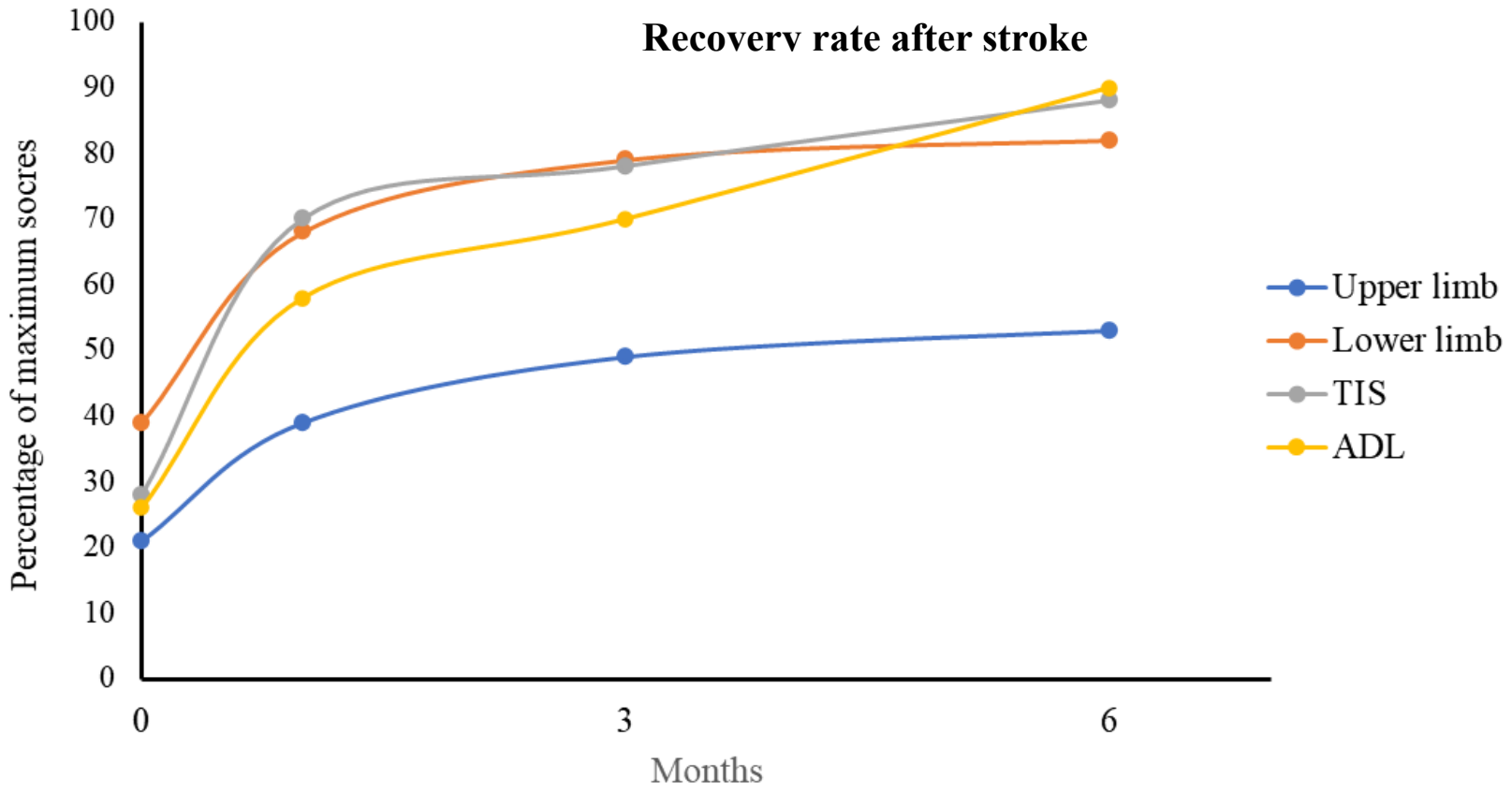


Figure 1-4: Graph on the recovery rate following stroke



Note: TIS: Trunk impairment scale; ADL: Activity of daily living. The figure has modified the illustration of the study by K.B. Lee et al. (2015)

Furthermore, previous studies (Hayward & Brauer, 2015; Serrada et al., 2016) have highlighted that the time allocated to UL therapy was minimal, with a considerable period of inactivity whereas it is known that early intervention within the first month after a stroke is essential and beneficial to the recovery of ULs and improving performance of daily activities (Kwakkel, van Peppen, et al., 2004; Wattchow et al., 2018).

1.5 Upper limb rehabilitation after stroke

Although medical advances have been made recently in stroke management, most post-stroke care relies on long-term rehabilitation services (Langhorne et al., 2009). Indeed, rehabilitation of hemiplegic upper limbs is a significant challenge for people after stroke, their clinicians, and researchers (Pollock et al., 2012; Stockley et al., 2019). Kleim and Jones (2008) outlined the ten principles of neuroplasticity as derived from decades of neuroscience research. These principles benefit clinicians in their planning of an upper limb rehabilitation program and are: “use it or lose it”, “use it and improve it”, specificity, repetition matters, intensity matters, time matters, salience matters, age matters, transference, and interference. The details of the ten principles are summarized in Figure 1-5.

Figure 1-5: Principles of Neuroplasticity

Note: Figure is modified from Keith and Jones (2008)

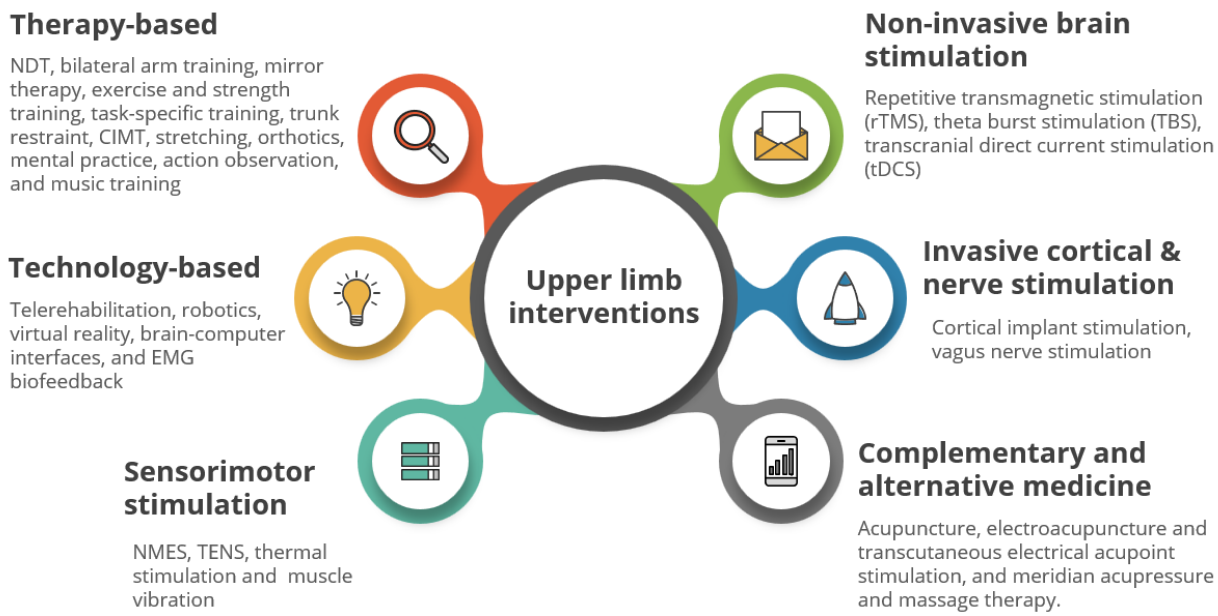
1.5.1 Types of upper limb rehabilitation interventions

This section presents an evidence-based review of various upper limb rehabilitation interventions for persons with stroke. According to the review by Saikaley et al. (2018), there are six categories of UL interventions in stroke rehabilitation: therapy-based rehabilitation, technology-based rehabilitation, sensorimotor stimulation, non-invasive brain stimulation, invasive cortical and nerve stimulation, and complementary and alternative medicine. Figure 1-6 presents an overview of the interventions classified under these six categories. In the first category, therapy-based intervention is interventions that include neurodevelopmental treatment (NDT), bilateral hand training, mirror therapy, exercise and strength training, task-specific training, trunk restraint, constraint-induced movement therapy (CIMT), stretching,

orthotics, mental practice, action observation and music training (Saikaley et al., 2018). The second category, technology-based intervention, includes telerehabilitation, wearables, robotics, virtual reality, brain-computer interfaces, and EMG biofeedback (Coscia et al., 2019; Saikaley et al., 2018).

Another category of rehabilitation interventions is sensorimotor stimulation. Sensorimotor stimulation aims to produce an adaptive response (Ayres, 1980) that is a more advanced, organized, flexible, and productive behavior than before stimulation (Farber, 1982). In sensorimotor stimulation, interventions use exteroceptors and proprioceptors rather than interceptors because behavior is believed to be learned from exteroceptive and proprioceptive stimulation (Go & Lee, 2016). Various modalities stimulate the exteroceptors to improve sensorimotor function (Heiniger & Randolph, 1981), and interventions in this category include neuromuscular electrical stimulation (NMES), transcutaneous electrical nerve stimulation, and thermal stimulation and muscle vibration (Saikaley et al., 2018).

Figure 1-6: Overview of Six Categories of UL Interventions



Note: The figure is modified from Saikaley et al. (2018)

The fourth category is non-invasive brain stimulation, which involves the use of a local magnetic field or electrical currents to facilitate or inhibit targeted brain areas (Coscia et al., 2019) and modulates cortical excitability (Nitsche & Paulus, 2000; Pascual-Leone et al., 1994; Rosenkranz et al., 2000). Among the non-invasive brain stimulation methods, transcranial magnetic stimulation (TMS) and transcranial direct-current stimulation (tDCS) are the most used (Hummel & Cohen, 2005).

There are two types of invasive stimulation: cortical stimulation and vagus nerve stimulation. Stimulation of the motor cortex was traditionally used to manage neuropathic pain. However, preclinical evidence in animals and clinical observations in patients with neuropathic pain also have shown motor improvement, so this technique has been adopted as an intervention for motor rehabilitation (Levy et al., 2008). Cortical stimulation involves a neurosurgical procedure performed through an extradural craniotomy to place a stimulation electrode on the dura mater of the motor cortex (Brown et al., 2008; Levy et al., 2016).

To date, research on cortical stimulation has only consisted of feasibility studies (Brown et al., 2008; M. Huang et al., 2008; Levy et al., 2008) because of its invasive nature and potential adverse effects. Vagus stimulation refers to the stimulation of the vagus nerve, activating the ascending neuromodulator networks that release plasticity-promoting neuromodulators such as acetylcholine and norepinephrine through the cortex (Engineer et al., 2019; Hays et al., 2013).

Last, the complementary and alternative medicine interventions used in stroke upper limb rehabilitation are acupuncture, electroacupuncture, transcutaneous electrical acupoint stimulation, meridian acupressure, and massage therapy.

1.5.2 Evidence for upper limb rehabilitation interventions in different phases of stroke

A review of the current evidence on the various upper limb rehabilitation interventions in different phases of stroke is presented in this section and reports the findings of several systematic reviews and clinical guidelines (Langhorne et al., 2011; Pollock et al., 2014; Saikaley et al., 2018; Wattchow et al., 2018). A systematic review and meta-analysis by Wattchow et al. (2018) reviewed the current evidence on the effects of UL interventions in the initial four weeks post-stroke. That review and meta-analysis selected 104 studies (83 RCTs and 21 non-randomized studies). Wattchow et al. (2018) listed three interventions that had sufficient evidence to demonstrate their effectiveness in improving upper extremity function: modified constraint-induced movement therapy (mCIMT), biofeedback, and electrical stimulation (Wattchow et al., 2018). Wattchow and colleagues (2018) also found that there was insufficient evidence to support or refute therapy-based interventions such as mirror therapy, bilateral arm training, strength training, orthosis, stretching, music therapy and passive ranging and technology-based interventions such as robotics and virtual reality training for routine use

in the acute phase of stroke. The current evidence discourages the routine use of Bobath therapy (Wattchow et al., 2018).

Several guidelines and reviews (Langhorne et al., 2011; Pollock et al., 2014; Saikaley et al., 2018) reviewed the effects of UL rehabilitation interventions beyond the acute phase of stroke. Table 1-1 summarizes and compares the evidence of each upper limb intervention according to the studies mentioned above (Langhorne et al., 2011; Pollock et al., 2014; Saikaley et al., 2018). Three interventions have been identified to have consistent evidence supporting their effectiveness: constraint-induced movement therapy (CIMT) or modified CIMT (mCIMT) (Langhorne et al., 2011; Pollock et al., 2014; Saikaley et al., 2018), task-specific training, and virtual reality training (Pollock et al., 2014; Saikaley et al., 2018). The literature is mixed in its support of the effectiveness of interventions such as mirror therapy, mental practice, stretching, bilateral training, music therapy, strength training, robotic, electromyography (EMG) biofeedback, electrical stimulation, repetitive transcranial magnetic stimulation (rTMS), and transcranial direct current stimulation (tDCS) (Langhorne et al., 2011; Pollock et al., 2014; Saikaley et al., 2018). In addition, three interventions - orthosis (Langhorne et al., 2011; Saikaley et al., 2018), Bobath therapy (Langhorne et al., 2011; Pollock et al., 2014; Saikaley et al., 2018), and acupuncture (Langhorne et al., 2011; Saikaley et al., 2018) are deemed to be unbeneficial in improving hemiplegic UL outcomes.

Table 1-1:*Effect of interventions in improving UL function*

Category	Interventions	Positive effects	Literature is mixed on positive effects	No beneficial effects
1. Therapy-based	Mirror therapy	■ ■	■	
	Mental practice	■ ■	■	
	Action observation	■		
	CIMT or mCIMT	■ ■ ■		
	Task-specific training	■ ■	■	
	Stretching	■		■
	Trunk restraint	■		
	Bilateral training		■ ■ ■	
	Strength training		■ ■	
	Music therapy		■	■ ■
	Bobath therapy			■ ■ ■
	Orthosis			■ ■
2. Technology-based	Virtual reality	■ ■		
	Robotics	■	■ ■	
	EMG biofeedback		■ ■	■
	Brain-computer interface		■	
3. Sensorimotor stimulation	Electrical stimulation	■	■	■
	Muscle vibration	■		
	Innocuous thermal stimulation		■	
4. Non-invasive brain stimulation	High-frequency rTMS	■		■
	Combining theta burst and rTMS	■		
	Transcranial direct stimulation		■ ■	
	Theta burst stimulation alone.			■
5. Invasive stimulation	Cortical and nerve stimulation		■	
6. Complementary therapies	Electroacupuncture with neuronavigation-assisted aspiration	■		
	Meridian acupuncture and massage	■		
	Acupuncture alone			■ ■

Referenced reviews:
■ Pollock et al. (2014) ■ Saikaley et al. (2018) ■ Langhorne et al., (2011)

Note: CIMT: constraint-induced movement therapy; mCIMT: modified constraint-induced movement therapy; rTMS: repetitive transmagnetic stimulation; EMG: electromyography

(collated from Langhorne et al., 2011; Pollock et al., 2014; Saikaley et al., 2018)

1.6 Rationale for home-based technology-based upper limb rehabilitation

As mentioned in the evidence review above, intensive task-specific training and CIMT or mCIMT approaches are effective interventions to improve the motor function of hemiplegic UL after stroke (Kwakkel, van Peppen, et al., 2004; Langhorne et al., 2011; Pollock et al., 2014; Saikaley et al., 2018; Wattchow et al., 2018). Nevertheless, some of these interventions do not apply to all stroke patient groups. For example, only stroke survivors with mild UL impairments can benefit from CIMT or mCIMT (Kwakkel et al., 2015; Stinear, 2010). Evidence-based reviews (Pollock et al., 2014; Wattchow et al., 2018) indicate that intensive training of the UL in the early phases of stroke (i.e. the first 1 to 3 months) is efficacious in improving the motor outcomes of a hemiplegic UL. Nevertheless, the cost of supervised therapy (the therapist's salary and the rehabilitation site) and hospitalization is high and cannot be sustained over the long term. Self-directed rehabilitation in the home helps to bridge the gap between providing intensive training and reducing the need for supervised therapy.

Increasingly, the emphasis is shifting from rehabilitation in the hospital to self-directed home-based training by empowering the patients and caregivers (Da-Silva et al., 2019; Fryer et al., 2016; Harris et al., 2009). Home-based training offers contextual learning and uses everyday objects that are relevant to the patients and can promote their recovery (Trombly & Wu, 1999). Our recent systematic review of home-based UL interventions confirmed this, indicating that home-based UL interventions were superior to clinic-based interventions in improving the function and perceived use of the affected upper limb (Toh, Chia & Fong, 2022). Nevertheless, supervised therapy in the home is costly and labor-intensive, which hinders the delivery of high-quality interventions (Rajsic et al., 2019; Visser-Meily et al., 2008).

Additional technological solutions such as wearable sensors, smartphone technologies and digital programs (i.e. videoconferencing tools) have been explored as beneficial alternatives to conventional therapy because they can make rehabilitation more accessible to stroke survivors

in the home (Chen et al., 2019; Selamat et al., 2022). These technologies provide flexibility in time and location and enable the therapy staff to monitor the patient remotely (Saadatnia et al., 2020). Home technology aims to reduce the need for direct therapist contact and thus alleviate saturated health services (Akbari et al., 2021). A home-based technology system offers a platform for lightly supervised and unsupervised therapies, reducing the need for a therapist's physical presence (Akbari et al., 2021). The recent COVID-19 pandemic has exacerbated the challenges of individuals needing rehabilitation (Andrenelli et al., 2020), and home technologies have been used to deliver rehabilitation services when face-to-face services were discouraged during the height of the COVID-19 pandemic (Chae et al., 2020; Falter et al., 2020).

Wearable technologies, or wearables, are promising examples of a novel technological system that can be deployed in the home. Wearables are electronic devices worn externally on the human body that can monitor individuals' activities without interrupting or restricting their movements (Parker et al., 2020; Rodgers et al., 2019). Some wearable devices can be connected to an application on smartphones for telerehabilitation, virtual reality training, and remote tracking of upper limb kinematic movements. The use of wearable devices in the home facilitates intensive self-directed training by providing feedback and allowing remote monitoring. In addition to permitting the convenience and comfort of exercising at home, wearable technologies offer the benefits of lower cost, greater flexibility, and portability over other conventional stroke therapies (Bonato, 2005; Fong & Chan, 2010; Wang et al., 2017).

1.7 Wearable technologies and telerehabilitation in stroke rehabilitation

1.7.1 Wearable technologies

Generally, wearable devices are applied as a health monitoring system and rehabilitation technology in healthcare. Wearables have two main functions: they either are used for measurement purposes to collect physiological parameters (e.g., blood pressure, oxygen saturation) to monitor health, predict future events and detect critical events (Asada et al., 2003; Banaee et al., 2013; Shaltis et al., 2006), or they are employed for treatment purposes such as providing feedback or reminders. For instance, wearable technologies are used to predict stroke risk by integrating wearable devices with machine-learning algorithms and electronic health records (Chen & Sawan, 2021). In rehabilitation, wearable technologies are used to measure body movement outside the laboratory and to correct posture (R. Lee et al., 2021; Wang et al., 2017). In addition, they are used in motor training by providing either real-time feedback to the users (Lee et al., 2021; Wang et al., 2017) or robotic rehabilitation assistance (passive or active-assistance) in movements through robotics (Marchal-Crespo & Reinkensmeyer, 2009).

Sensors are commonly used in most wearable devices. Examples of wearable sensors include microelectromechanical systems containing an accelerometer, gyroscope and/or magnetometer (Parker et al., 2020); fabric and body-worn sensor networks (Wang et al., 2018); pressure sensors (Davies et al., 2016; Munoz-Organero et al., 2017) and electromyography sensors. In stroke rehabilitation, wearable devices are applied in areas such as virtual reality training (Laver et al., 2015), sensorimotor stimulation (Choudhury et al., 2020; Howlett et al., 2015; Palmcrantz et al., 2020), activity trackers (Da-Silva et al., 2019; Da-Silva, van Wijck, et al., 2018; W.X.J. Wei, Fong, Chung, Cheung, & Chow, 2019; W.X.J. Wei, Fong, Chung, Cheung, Myint, et al., 2019) and robotics (Kwakkel et al., 2008; Rodgers et al., 2019; Thalman & Artemiadis, 2020). Our recent scoping review for this thesis found that most research on wearable technologies that were applied in the home has focused on improving the hemiplegic

UL, but the use of smartphone technology in wearable-based virtual reality training is underexplored (Toh, Fong et al., 2023).

1.7.2 Smartphone telerehabilitation

Telerehabilitation (TR) refers to the remote delivery of rehabilitation services using information and communications technology (Brennan et al., 2011; Kairy et al., 2009; McCue et al., 2010). Telerehabilitation substitutes for traditional in-person programs when rehabilitation infrastructures are inaccessible because of geographical locations, and it reduces the travel time for patients to access their services (Peretti et al., 2017). Previously, TR was used to bridge the geographic separation between service providers and patients, such as in rural regions (Cason, 2009). Nevertheless, studies have demonstrated that TR helps to resolve some existing service problems, such as improving access to rehabilitation services, preventing care delays (Cason, 2014) and reducing the impact of shortages of rehabilitation professionals in underserved areas (Cason, 2012).

The development of wearable sensing technologies can be integrated and applied in motor rehabilitation, in which monitoring and treatment outcomes can be addressed outside of clinical settings (Hung & Fong, 2019). Remotely monitored programs supported by telerehabilitation and wearables help patients develop exercise behavior in a real-life environment outside of clinical sessions (Rawstorn et al., 2016). The high global ownership of smartphones provides many opportunities for telerehabilitation (Moral-Munoz et al., 2021). Nonetheless, a systematic review by Hung and Fong (2019) revealed that the extant studies on the effectiveness of smartphone-based telerehabilitation are few, and it is unknown whether smartphone technology is useful for the delivery of home-based TR programs.

1.8 Mechanisms of wearable technologies

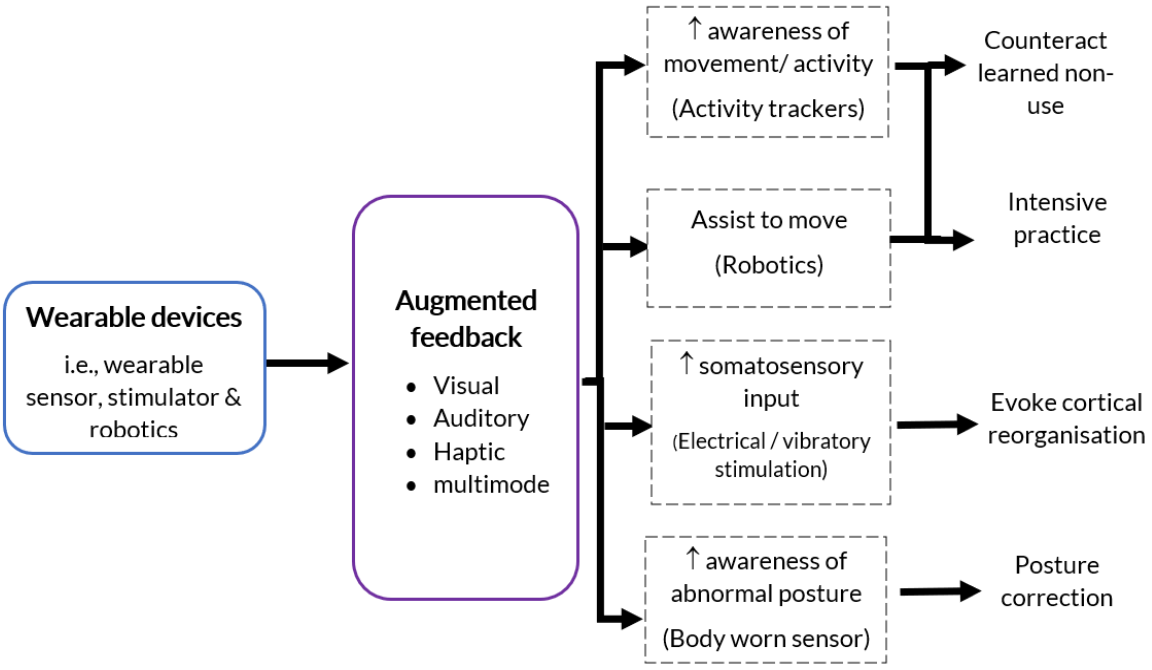
Wearable devices are considered to be effective interventions for promoting the recovery of hemiplegic ULs because they provide augmented feedback to the wearer, which is crucial for motor learning (Kim et al., 2021; Lee et al., 2021; Schmidt et al., 2018). Augmented feedback refers to the extrinsic information provided by an external source outside the body, and it encompasses feedback that is visual, auditory, haptic (tactile) and multimodal (two or more modes) (Jakus et al., 2017; Moinuddin et al., 2021). In general, wearable technologies provide four types of feedback: visual, auditory, haptic, and summary feedback. Visual, auditory, and haptic feedback can be introduced in real-time, whereas summary feedback refers to delayed visual feedback that is provided as an overview of performance after multiple trials (Timmermans et al., 2009). Feedback timing can be introduced concurrently or terminally (Molier et al., 2010). Concurrent feedback refers to feedback delivered during a prescribed movement, whereas terminal feedback refers to the feedback prompt being postponed until the movement or task is completed (Schmidt & Lee, 2005). Concurrent feedback is suitable for individuals in the initial skill acquisition phase whose skill proficiency is low, whereas terminal feedback is used for highly proficient individuals (R. Lee et al., 2021; Wang et al., 2017).

External feedback, such as augmented feedback, is vital because it enhances motor learning and sustains the person's motivation during learning (Van Vliet & Wulf, 2006). External feedback is especially helpful for individuals with stroke for their motor learning because their body's internal feedback mechanisms (e.g., proprioceptive cues) are weakened or damaged after an injury to the brain (Timmermans et al., 2009; Van Vliet & Wulf, 2006). Traditionally, this kind of external feedback is provided by therapists to facilitate motor re-education in people who had a stroke (Wang et al., 2017), but that mode of training is time-consuming and challenging to carry out consistently at home (Wang et al., 2017). As an alternative, a wearable device can provide the necessary external feedback to increase the individual's awareness of

correct posture and movement patterns and to provide corrective feedback during functional task execution in the absence of the therapist (R. Lee et al., 2021; Wang et al., 2017).

However, the effectiveness of the various types of feedback has remained debatable in previous studies, with no single type of feedback being identified as the most effective for motor learning (Ronsse et al., 2011; Sigrist et al., 2013). Nevertheless, one consensus among the past studies was that augmented multimodal feedback (a combination of two or more feedback modes) is perceived to be more effective than a single mode is for delivering feedback in motor learning (Moinuddin et al., 2021). One reason for the superior effectiveness is that when feedback from different modes is presented simultaneously, the human brain processes the information faster (Moinuddin et al., 2021). Therefore, the wearable device can provide multimodal augmented feedback, which enhances the user's motor learning process. Furthermore, unlike traditional methods of monitoring a patient's adherence to therapy(i.e., an activity logbook or checklist), wearable sensors can trigger sensory reminders to the user to move, thereby promoting engagement and adherence to treatment in the home setting (Kim et al., 2021). In stroke rehabilitation, wearable devices are applied in various interventions, such as robotics, activity trackers, and stimulation, and they provide augmented feedback to achieve various therapy outcomes. For example, wearable devices are used for activity tracking to increase the users' awareness of their activity and movement and encourage them to move their affected arm more to counteract learned nonuse. In another example, wearable devices can be used in robotics to provide haptic feedback and to assist in passive movement, thereby enabling intensive practicing with the hemiplegic arm. Figure 1-7 summarizes the use of augmented feedback in various interventions that have applied wearable devices, according to studies by R. Lee et al. (2021) and Wang et al. (2017).

Figure 1 -7: Mechanisms of Wearable Devices



Note: Figure modified from R. Lee et al. (2021) and Wang et al. (2017)

1.9 Theoretical framework of home-based rehabilitation using wearable technologies

Sustaining a person's motivation with rehabilitation is challenging, especially in an unsupervised condition such as the home environment (Cramer et al., 2019). A previous review by McLean et al. (2010) reported non-compliance levels as high as 70% in traditional home rehabilitation activities. As an alternative, wearable technologies can provide telerehabilitation and offer remote monitoring from the therapist in a home-based rehabilitation program. Indeed, in an unstructured environment such as the home, remote monitoring from the therapist can be essential to maintain the patient's motivation and adherence to training because such training

promotes the interaction between therapist and client interactions and provides timely feedback (Evangelista et al., 2015).

Given the challenges inherent in providing home-based rehabilitation, it is worthwhile to have a theoretical framework to guide the use of wearable technologies in the home context to ensure that the needs of the stroke population are met. Unfortunately, the existing telehealth framework only focuses on the stroke population's physical rehabilitation demands and does not explore beyond that (Akbari et al., 2021) to consider the real-life needs of post-stroke individuals and the multi-faceted needs of other stakeholders (Akbari et al., 2021). Akbari and colleagues (2021) proposed a conceptual framework that provides a unified, interoperable solution that lays a foundation for home-based rehabilitation using robotic technology and supports other needs, such as socialization and independence, for daily activities for persons with stroke. Their framework's strength is that it addresses the multi-faceted needs of the various stakeholders in post-stroke rehabilitation, such as healthcare professionals, patients, and researchers (Akbari et al., 2021). Although this framework relates to home-based robotic technology, it shares a similar concept of applying wearable technologies in the home environment. Hence, this PhD thesis research adoptand modifies the framework proposed by Akbari et al. (2021) to describe a framework that can guide home-based rehabilitation using wearable technologies, as is illustrated in Figure 1-8.

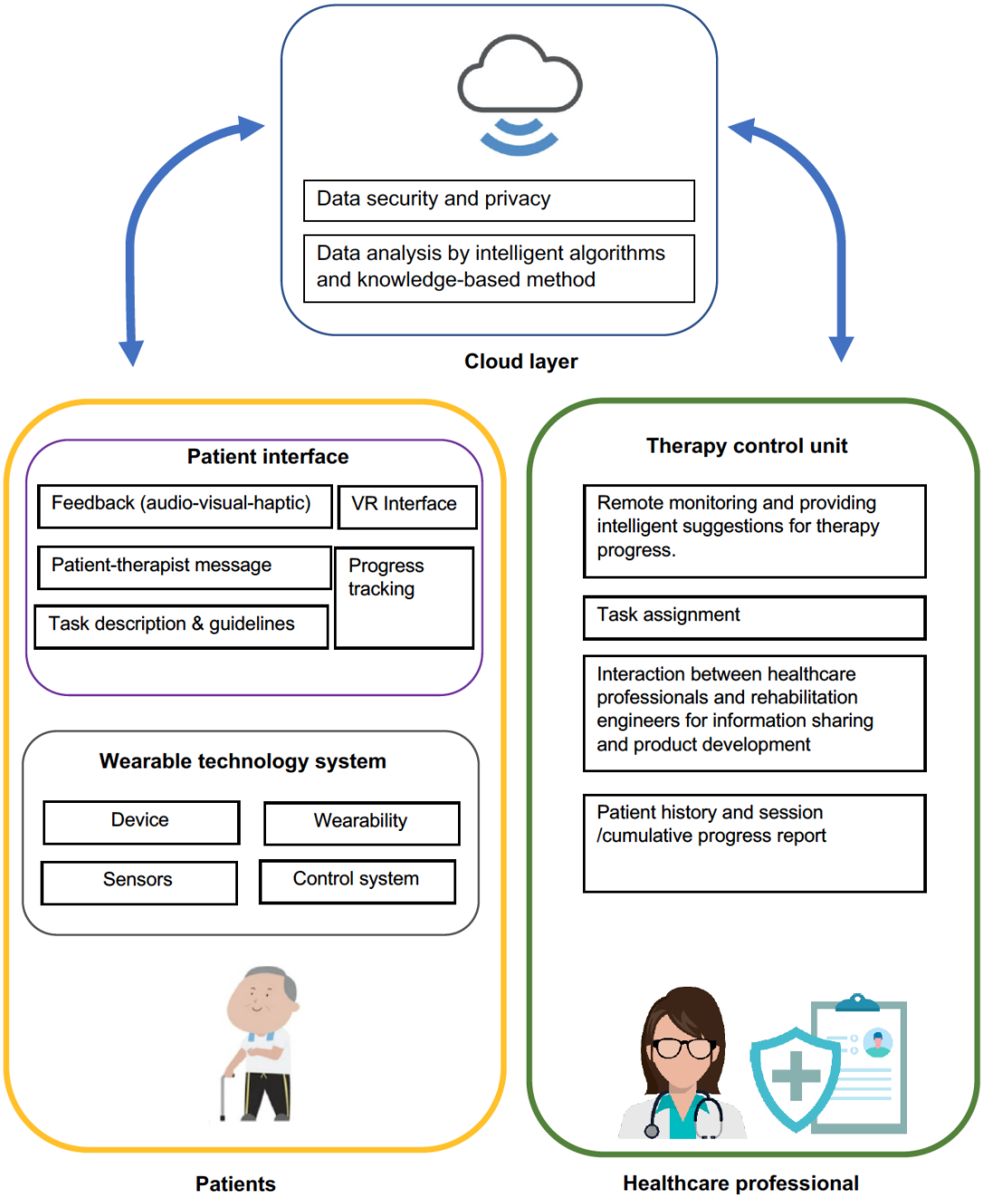
The central concept of this framework for wearables is based on a multi-agent information and communication technology (ICT) system that allows interaction among patients, healthcare professionals such as therapists, and engineers over the platform provided (Akbari et al., 2021). Those interaction utilizes a cloud-based system for computing, storing, and analyzing data collected by wearable devices. Eventually, the acquired data from the wearable devices form a large data set that can be analysed using a machine-learning model to aid in future predictive models for rehabilitation outcomes and to assist clinicians in future decision-

making regarding the management of patients and the coordination of their expectations (Shtar et al., 2021). Clearly, safety measures must be taken to ensure data confidentiality and security, given the sensitive nature of medical data (Sahu et al., 2020; Rodgers et al., 2019).

From the patient's perspective, a consideration of the device's wearability is critical. Wearability refers to the interaction of a wearable device with the human body (Gemperle et al., 1998), and it influences the users' usability - their acceptance and adherence to using the device long term (Wang et al., 2017). A high degree of comfort, unobtrusive size, and ease of wear are essential wearability factors, as highlighted in previous studies (Cherry et al., 2017; Wang et al., 2017). In addition, the device must perform consistently; otherwise, patients will lose confidence in the device's effectiveness and abandon it. Furthermore, the device's performance, in terms of its reliability and durability, is considered to be a significant predictor of assistive technology abandonment (Phillips & Zhao, 1993). Therefore, functional testing and appropriate training in device use are essential before implementing a wearable device in the clinical setting. Finally, timely technical support is pivotal to maintaining positive user experiences with home-based technologies (Chen et al., 2020).

In this proposed framework for wearable neurorehabilitation devices, essential elements in the therapy control unit include remote monitoring, task assignments and interactions with other professionals. Remote monitoring, such as in telerehabilitation, allows the therapists to review the participant's progress and adjust the therapy prescription at their convenience while maintaining close therapist-client interactions and communication.

Figure 1 -8: Theoretical Framework Guiding Home-Based Rehabilitation Program Using Wearable technologies



Note: Figure is adapted from the framework by Akbari and colleagues

Task assignments should be standardized to avoid confusion and ambiguity and ensure mutual understanding among all parties (Akbari et al., 2021), and they should allow any customization needed in order to meet individual needs and provide a level of consistency that will survive repetitive use over time. This communication mode enables healthcare professionals to clarify issues or ambiguities, gain additional expertise, or discuss possible treatment plans (Akbari et al., 2021), and it allows healthcare professionals to work closely with rehabilitation engineers to refine the wearable technology system

1.10 Research rationale

The trend of increasing numbers of publications in wearable technologies highlights the growing interest in this field of research in stroke rehabilitation (Kim et al., 2021; Parker et al., 2020; Toh, Fong et al., 2023). However, Wang et al. (2017) noted that at the time of their review, most wearable systems were prototypes in the feasibility stage, and few had been evaluated in clinical trials. In addition, previous research found a lack of high-quality evidence for the clinical effectiveness of wearable technologies for home-based rehabilitation (Kim et al., 2021; Parker et al., 2020). Most of the research conducted in the past has focused on wearable sensors and mainly on those used for evaluation and not for treatment (Kim et al., 2021; Maceira-Elvira et al., 2019; Rodgers et al., 2019).

Some wearables can provide augmented feedback, which can be used to guide patients in their daily self-directed training (Kim et al., 2021; Wang et al., 2017). Such feedback from the wearables makes them an effective tool for rehabilitation interventions for people with stroke beyond just their measurement capabilities (Toh, Fong et al., 2023). Furthermore, existing evidence from previous reviews was skewed toward rehabilitation in hospitals or laboratories, thus requiring a rehabilitation specialist (Peters et al., 2021; Rodgers et al., 2019), and few have

focused on self-directed rehabilitation in the home (Rodgers et al., 2019). Therefore, the effect of using wearable devices on upper limb rehabilitation at home has remained unclear in the current literature (Kim et al., 2021; Parker et al., 2020; Rodgers et al., 2019; Toh, Fong et al., 2023). Additional research is needed to investigate the clinical effects of wearable technology systems (Wang et al., 2017) and their efficacy in supporting home-based rehabilitation (Rodgers et al., 2019). Moreover, managing patient compliance in home-based rehabilitation remains challenging, as highlighted by McLean et al. (2010), who reported a high rate of non-adherence among patients. A key contributing factor is the lack of close monitoring by therapists, which diminishes patient motivation. Wearable technology offers a promising solution by enabling remote monitoring, but Chen et al. (2019) caution that multiple factors influence the successful implementation of technology-assisted interventions. Therefore, to ensure the successful implementation of wearable-based interventions at home, it is crucial to identify the essential design elements that will enhance patient engagement and adherence.

1.10.1 Addressing research gaps

The systematic review conducted by Wang et al. (2017) indicated that wearable devices should support therapies that are interactive and engaging. In virtual reality and telerehabilitation, therapies can be interactive and enjoyable, as patients receive stimulation through real-time visual and auditory feedback about their performance (H. S. Lee et al., 2019; Weiss et al., 2006). However, the feature of an interactive mode is generally absent in several studies that used wearables in upper limb interventions (Choudhury et al., 2020; Da-Silva et al., 2019; Da-Silva, Moore, & Price, 2018; Palmcrantz et al., 2020; Sullivan et al., 2012; W. X. J. Wei, Fong, Chung, Cheung, & Chow, 2019; W. X. J. Wei, Fong, Chung, Myint, et al., 2019; Whitford et al., 2020). This thesis first investigates the current evidence of home-based upper limb intervention and the use of wearable technology for home-based rehabilitation for the

stroke survivors through two comprehensive reviews (Study 1 and Study 2). Following the thesis proposes a wearable device,- 'Smart Reminder', with two unique features that are absent in previous wearable studies (Ballester et al., 2017; Choudhury et al., 2020; Cramer et al., 2019; Da-Silva et al., 2019; Da-Silva, Moore, & Price, 2018; Palmcrantz et al., 2020; Sullivan et al., 2012; W. X. J. Wei, Fong, Chung, Cheung, & Chow, 2019; W. X. J. Wei, Fong, Chung, Myint, et al., 2019; Whitford et al., 2020; Wittmann et al., 2016), as well as conducts experiments to evaluate the usability, feasbility and efficacy of the wearable device for hemiplegic UL recovery in the home through Studies 3 to 5

First, the Smart Reminder, or SR, is a wristwatch that has inertial sensors such as an accelerometer and a gyroscope to track rotational movement, whereas previous studies (W. X. J. Wei, Fong, Chung, Cheung, & Chow, 2019; W. X. J. Wei, Fong, Chung, Myint, et al., 2019; Whitford et al., 2020) used just an accelerometer to track arm activity. Unlike the accelerometer, the gyroscope measures rotational and angular projections, such as the range of motion (Aroganam et al., 2019; Passaro et al., 2017). Combining the accelerometer and gyroscope filters errors and increases accuracy in measuring angles (Aroganam et al., 2019).

Another unique feature of the SR device is that it connects to a smartphone's telerehabilitation application (app) to provide interactive therapy and remote monitoring. The wristwatch's inertial sensors capture the user's movements during training, and the smartphone's telerehabilitation app shows the user's prescribed exercises and real-time performance (i.e. UL range of motion and repetitions). The features of interactive therapy and remote monitoring promote patient involvement and support the patient's motivation, which is essential for unsupervised home interventions. The therapist's remote monitoring reduces the risk of noncompliance by fostering interactions between the therapist and the client and also by providing timely feedback (Evangelista et al., 2015). Furthermore, the SR device provides multimodal augmented feedback through reminders (via sounds and vibrations) and

telerehabilitation (visual and sound) features. The device's multimodal augmented feedback enhances the motor learning process in stroke survivors, as discussed in section 1.8.

The SR device was developed as an evolution of the earlier 'Remind to Move' device (Fong et al., 2011; W. X. J. Wei et al., 2019; X. Wei, 2018), which prompts patients to engage their affected arm in activities of daily living (ADLs). Similar to 'Remind to Move' device, the SR device use vibration and sounds to remind users to perform prescribed exercises at scheduled times and regular intervals, as customized by the therapist. In addition, the SR's telerehabilitation app includes exercise videos featuring simple functional tasks like wiping a table, pouring water, and picking up a cube, etc., along with standard range of motion (ROM) exercises for the upper limb. A notable advancement of the SR device is its integration with a smartphone telerehabilitation interface, offering a more portable and accessible visual display- a feature not commonly found in the existing wearable studies (Ballester et al., 2017; Cramer et al., 2019; Wittmann et al., 2016) which primarily used visual displays such as computers, laptops, and televisions. Over the past decade, smartphone-based telerehabilitation has emerged and grown exponentially (Moral-Munoz et al., 2021). Embedded sensors in smartphones or wearables can provide tremendous information concerning a person's health status and behavior patterns (Moral-Munoz et al., 2021). Smartphones are more portable than the digital screens mentioned above, allowing people with stroke to rehabilitate at their preferred location and with minimum setup required (Toh, Gonzalez, & Fong, 2023). According to our scoping review (Toh, Fong et al., 2023), little research has yet explored integrating smartphone software applications and wearable devices to provide upper limb training for stroke survivors at home. Hence, this PhD research is one of a kind and comes at a time when the current clinical validation of integrating smartphone and wearable technologies to provide UL rehabilitation in the home is limited.

1.11 Research significance and scope

Stroke survivors view the recovery of their upper limbs as being crucial (Barker & Brauer, 2005). Advances in technology offer accessible and affordable rehabilitation options to promote rehabilitation activities without increasing the demand for therapists' time (Demain et al., 2013) and alleviating constraints on healthcare resources. This PhD thesis aims to make three key research contributions in the application of wearable technologies for home-based rehabilitation to promote hemiplegic UL recovery for the stroke population: (a) to identify the elements required in the treatment design and the wearable technologies for implementing home-based rehabilitation, (b) to consolidate the current evidence on the application of wearable technologies in home-based stroke rehabilitation, and (c) to explore the feasibility and evaluate the efficacy of a proposed wearable device for use as an alternative, self-directed UL treatment for the stroke population.

Because the research for this thesis centered on home-based intervention, the scope of the research focused on people who have suffered a stroke for a minimum of three months previously and who resided in community dwellings. The proposed Smart Reminder device was designed and developed by The Hong Kong Polytechnic University, with the target audience being the local Hong Kong population.

1.12 Research aims and questions

This PhD thesis research seek to evaluate the efficacy of a proposed wearable device, the Smart Reminder, which has telerehabilitation features that are designed to provide home-based self-directed UL training for persons with stroke and thereby address the research gaps mentioned above. The overarching research questions are as follows.

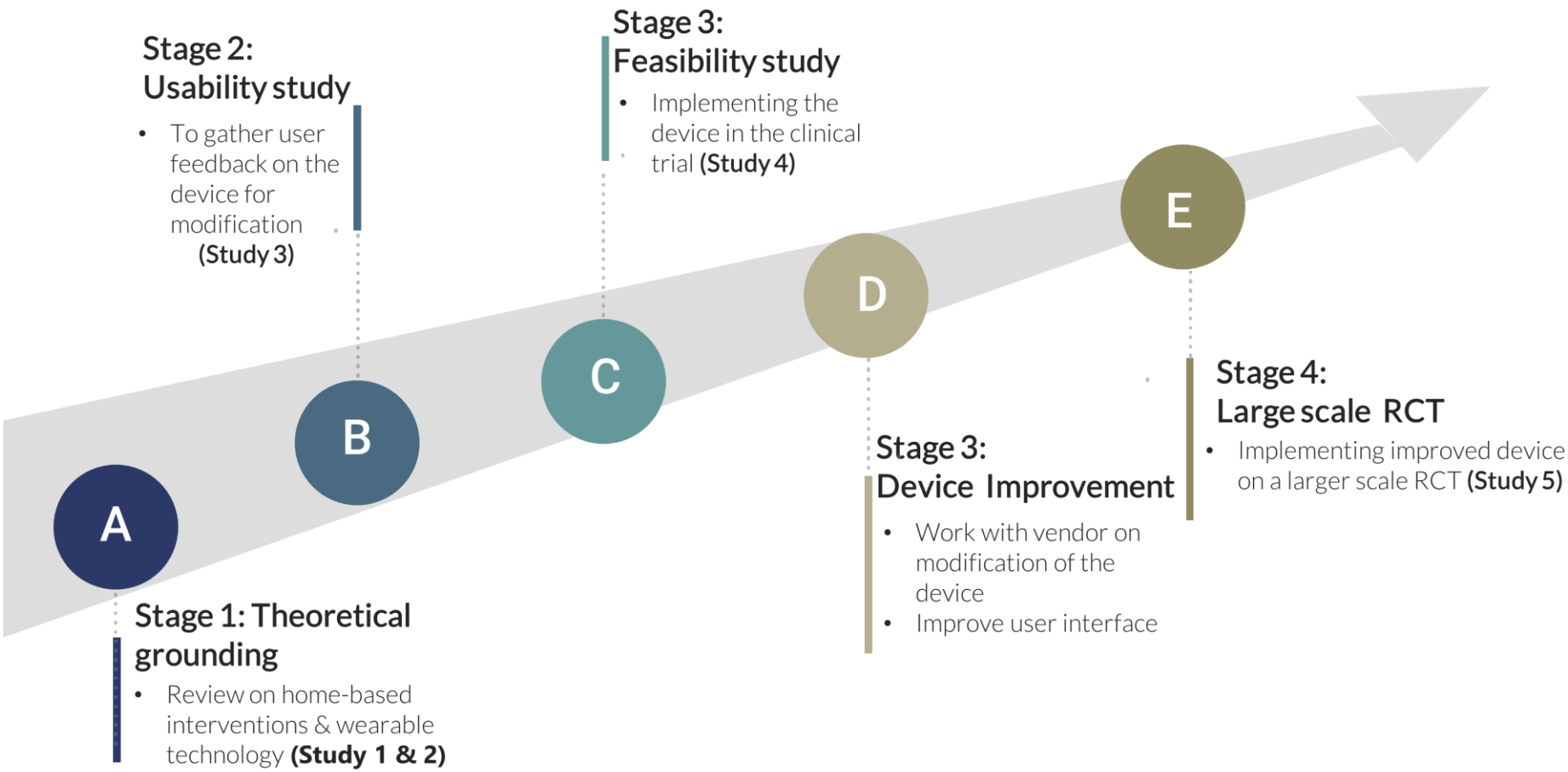
Research questions	Addressed by
• What are the essential elements needed for successful technology-based upper limb rehabilitation for persons with stroke in the home setting?	Study 1: A systematic review and meta-analysis of home-based upper limb rehabilitation after stroke
• What is the current evidence for the application of wearable technologies in home-based rehabilitation for persons with stroke?	Study 2: A scoping review of wearable technologies in home-based stroke rehabilitation
• How usable and feasible was the 'Smart Reminder' (SR)– our study's proposed wearable device, as a tool for hemiplegic UL intervention in stroke rehabilitation?	Study 3: Usability study of a Smart Reminder as a home-based UL intervention for stroke survivors
	Study 4: The effect of the Smart Reminder as a home-based UL intervention for stroke survivors—a pilot feasibility study
• Is the Smart Reminder, proposed in this study, more efficacious in promoting hemiplegic UL recovery in persons with stroke than conventional therapy that uses a sham device after treatment and at follow-up?'	Study 5: The effects of a wearable device, the Smart Reminder, as a home-based UL intervention for stroke survivors—a randomized controlled trial

1.13 Research methodologies

In this PhD research, a mixed methods approach with both quantitative and qualitative methodologies is used to evaluate the efficacy of the proposed Smart Reminder device in providing an efficacious upper limb rehabilitation program for persons with stroke. This PhD research have four stages and consisted of five studies that are conducted to meet the research aim and address the research questions. A brief overview of the overall study design is included here (see Figure 1-9), with the full details of the methodologies applied in the five studies explained in the subsequent chapters of this thesis.

In Phase One, the theoretical foundation of this PhD research is addressed by Studies 1 and 2. Following Phase Two, a usability study (Study 3) has been conducted with the stroke participants regarding their acceptance of the proposed SR device. In Phase Three, a proof-of-concept pilot feasibility study (Study 4) is conducted to assess the clinical utility of the SR device. Simultaneously, the SR device has been enhanced and modified on the basis of the results of Study 3. Last, in Phase Four, the primary study of this PhD thesis (Study 5), a randomized controlled trial, has been conducted to evaluate the efficacy of the SR device in improving the hemiplegic arm function of persons with stroke.

Figure 1-9: Overall stages of this PhD's study



1.14 Outline of thesis

This thesis consists of seven chapters that include four published manuscripts and one manuscript submitted for peer review. The seven chapters are outlined below.

Chapter 1: Introduction

In Chapter 1, I describe the issues that motivated this thesis and present the background of stroke upper limb rehabilitation, the application of wearable technologies, and the gaps in this field that formulated the research rationale and aim. The research methodology of this PhD research is also explained.

Chapter 2: Effectiveness of home-based upper limb rehabilitation in stroke survivors: a systematic review and meta-analysis

Chapter 2 presents the results of a systematic review and a meta-analysis that were conducted to examine the current evidence on the effects of existing home-based upper-limb rehabilitation interventions for hemiparetic UL recovery in stroke survivors. Along with Chapter 3, this chapter presents the background knowledge used for planning the empirical studies described in Chapters 4 through 6.

Chapter 2 has been published as:

Toh, S. F. M., Chia, P. F., & Fong, K. N. K. (2022). Effectiveness of home-based upper limb rehabilitation in stroke survivors: A systematic review and meta-analysis. *Frontier in Neurology*, 13, 964196. doi:10.3389/fneur.2022.964196.

Chapter 3: Application of Home-Based Wearable Technologies in Physical Rehabilitation for Stroke: A Scoping Review

Chapter 3 presents a scoping review that examines the current evidence of wearable technologies in stroke rehabilitation in the home setting. This chapter joins Chapter 2 in

presenting the background knowledge for planning the empirical studies described in Chapters 4 through 6.

Chapter 3 has been published as:

Toh, S. F. M., Fong, K. N. K., Gonzalez, P. C., & Tang, Y. M. (2023). Application of home-based wearable technologies in physical rehabilitation for stroke: A scoping review. *IEEE Transactions on Neural System and Rehabilitation Engineering,* Pp. doi:10.1109/tnsre.2023.3252880.

Chapter 4: Usability of a wearable device for home-based upper limb telerehabilitation in persons with stroke: A mixed-methods study

Chapter 4 describes the usability study (Study 3) that was carried out to identify three main issues regarding the usability of the proposed SR device: (a) the functions and features of the SR device, and which features were valued and which were disliked by the users; (b) the participants' perceptions of the usability and acceptability of the wristwatch; and (c) features in the device that required further modification. The study was a mixed-methods study with quantitative and qualitative approaches to explore stroke users' perspectives on using the proposed SR device. The results of this study led to the enhancement and modification of the device for the main study described in Chapter 6.

Chapter 4 has been published as:

Toh, S. F. M., Gonzalez, P. C., & Fong, K. N. K. (2023). Usability of a wearable device for home-based upper limb telerehabilitation in persons with stroke: A mixed-methods study. *Digital Health*, 9, 20552076231153737. doi:10.1177/20552076231153737.

Chapter 5: 'Smart reminder': A feasibility pilot study on the effects of a wearable device treatment on the hemiplegic upper limb in persons with stroke

Chapter 5 reports a pilot randomized crossover trial (Study 4) that was conducted to examine the feasibility and potential therapeutic effects of the proposed SR wearable device, which was integrated with a smartphone-based telerehabilitation system to provide UL rehabilitation to stroke survivors at home. The results of this study contributed to the sample size calculation for the main study described in Chapter 6.

Chapter 5 has been published as:

Toh, F. M., Lam, W. W., Gonzalez, P. C., & Fong, K. N. 'Smart reminder': A feasibility pilot study on the effects of a wearable device treatment on the hemiplegic upper limb in persons with stroke. *Journal of Telemedicine and Telecare*, 0(0), 1357633X231222297. doi:10.1177/1357633x231222297.

Chapter 6: Effects of a Wearable Device Treatment on the Hemiplegic Upper Limb in Persons with Stroke: A Randomized controlled Trial

Chapter 6 discusses a randomized controlled trial (Study 5) that was conducted to examine the effectiveness of the proposed SR wearable with telerehabilitation features to provide home-based self-directed UL training for persons with stroke. This study compared the effects from the SR intervention with those from conventional therapy using a sham device in improving the hemiplegic UL function for stroke survivors.

Toh, F. M., Lam, W. W., Gonzalez, P. C., & Fong, K. N. (2024). 'Smart reminder': A Randomized Controlled Trial on the effects of a wearable device treatment on the hemiplegic upper limb in persons with stroke (submitted to Neurorehabilitation Neural Repair for peer review).

Chapter 7: Discussion and Conclusion

Chapter 7, the final chapter, provides a synthesized and summarized discussion of the research findings from all the studies undertaken as part of this thesis. This chapter concludes the findings of this thesis and outlines the clinical implications of using wearable technology in stroke UL rehabilitation, the limitations of this thesis, and recommendations for future research.

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Chapter 2: Effectiveness of home-based upper limb rehabilitation in stroke survivors: a systematic review and meta-analysis

This chapter reviewed the evidence on the effectiveness of home-based upper limb interventions. The author of this thesis published this chapter as a review article in Frontiers in Neurology in September 2022. The citation for the systematic review and meta-analysis was:

Toh SFM, Chia PF, Fong KNK. Effectiveness of home-based upper limb rehabilitation in stroke survivors: A systematic review and meta-analysis. *Frontiers in neurology*. 2022;13:964196-964196.

The manuscript, included below, has been formatted according to APA 6th to align with the thesis format. References are provided at the end of the thesis.

2.1 Abstract

Background: Home-based training is an alternative option to provide intensive rehabilitation without costly supervised therapy. Though several studies support the effectiveness of home-based rehabilitation in improving hemiparetic upper limb function in stroke survivors, a collective evaluation of the evidence remains scarce. **Objectives:** This study aims to determine the effects of home-based upper limb rehabilitation for hemiparetic upper limb recovery in stroke survivors. **Methods:** The databases of the Cochrane Library, MEDLINE, CINAHL, and Web of Science were systematically searched from January 2000 to September 2020. Only randomised, controlled, and cross-over trials that evaluated the effects of home-based upper limb interventions were selected. The Pedro scale was used to assess the methodological quality of the studies. A meta-analysis of the upper limb function outcomes was performed by calculating the mean difference/standardised mean difference using a fixed/random effect model. **Results:** An initial search yielded 1,049 articles. Twenty-six articles were included in the review. The pooled evidence of the meta-analysis showed that home-based upper limb intervention was more effective in improving upper limb function (SMD: 0.28, 95% CI (0.12, 0.44), I^2=0%, p<0.001, fixed effect model) than conventional therapy. When comparing two types of home-based interventions, subgroup analysis revealed that home-based technology treatment – electrical stimulation – provided more significant improvement in upper limb function than treatment without the use of technology (SMD: 0.64, 95%CI (0.21, 1.07), I^2=0%, p=0.003, random effect model). **Conclusion:** The beneficial effects of home-based upper limb interventions were superior to conventional therapy in improving function and perceived use of the hemiparetic upper limb in daily activities. Among the home-based interventions, home-based electrical stimulation seemed to provide the most optimal benefits.

Keywords: Home-based interventions, hemiparetic upper limb, rehabilitation, stroke

2.2 Introduction

Upper limb disability in stroke survivors poses a significant challenge to rehabilitation practitioners (Brauer, Hayward, Carson, Cresswell, & Barker, 2013). Stroke survivors, carers, and healthcare professionals perceived that further research in upper limb rehabilitation is one of their top priorities (Pollock, St George, Fenton, & Firkins, 2014). Only 15% of the stroke survivors would gain complete functional recovery in their motor functions (Hendricks, van Limbeek, Geurts, & Zwarts, 2002), while 33 to 60% had little or no function in their hemiplegic arm in the chronic phase (Kwakkel & Kollen, 2013). Timing, intensity, and task-specific practice are critical elements that facilitate the recovery of the hemiparetic upper limb after a stroke (Pollock et al., 2014; Timmermans, Seelen, Willmann, & Kingma, 2009; Van Peppen et al., 2004). However, the intensity of rehabilitation in an outpatient setting after discharge is usually inadequate (Wei et al., 2019).

Home-based rehabilitation offers an alternative to providing intensive training without costly supervised outpatient rehabilitation (Saadatnia, Shahnazi, Khorvash, & Esteki-Ghashghaei, 2020) and, more importantly, as a buffer during the transition from inpatient to rehabilitation services in the community. Increasingly, technological innovation has been deployed to provide home-based rehabilitation (Chen et al., 2019a) as these technologies offer flexibility in time and location and allow remote monitoring from the therapist (Saadatnia et al., 2020). Furthermore, the recent Covid-19 pandemic has escalated this urgency to use home-based technologies to deliver the core components of rehabilitation as in-person services were discouraged from curbing the spread of the pandemic (Chae, Kim, Lee, & Park, 2020; Falter, Scherrenberg, & Dendale, 2020).

Home-based upper limb (UL) rehabilitation refers to upper limb interventions conducted in the patient's home (permanent address, including other supported or sheltered

home). The intervention is either self-directed or therapist-supervised and is conducted either with or without technology. Technology-assisted interventions include virtual reality, telerehabilitation, robotics, interactive video games, wearable devices, transcranial direct current stimulation, brain-computer/machine interfaces, and electrical stimulation (Chen et al., 2019a; Coscia et al., 2019a). 'No technology' interventions refer to mirror therapy, mental practice, music therapy, constraint-induced movement therapy (CIMT), bilateral upper limb training, task-specific training, and strength training (Pollock et al., 2014).

Previous reviews and meta-analyses supported the effectiveness of home-based rehabilitation services in improving the patients' performance in their daily living activities (ADL), physical function, and quality of life (Chi, Huang, Chiu, Chang, & Huang, 2020; Hillier & Inglis-Jassiem, 2010; Trialists, 2003). These reviews adopt a broad view of the effect of the home-based intervention on the stroke survivors' overall functional performance using outcome measures such as the Barthel Index (BI) and Functional Independence Measure (FIM). While contributing valuable knowledge on home-based stroke rehabilitation, the treatment effect on the stroke survivors' hemiplegic upper limb remained unclear.

The effectiveness of home-based upper limb rehabilitation interventions to promote the motor recovery of the hemiplegic upper limb among stroke survivors is supported by several previous studies (Dodakian et al., 2017; Duncan et al., 2003; Hsieh et al., 2018; Wei et al., 2019). Nevertheless, a collective evaluation of the available evidence in this area remained scarce. To our knowledge, there is one Cochrane review undertaken in 2012 (Coupar, Pollock, Legg, Sackley, & van Vliet, 2012), which reviewed the effects of home-based therapy targeting upper limb recovery after stroke. Due to the lack of information available, only four RCT studies were included in the review. This Cochrane review (Coupar et al., 2012) found that the effectiveness of a home-based upper limb rehabilitation was not superior to that of usual care. With insufficient good-quality evidence, the impact of home-based therapy programs for arm

recovery in stroke survivors remained inconclusive (Coupar et al., 2012). As this review was conducted a decade ago, the results of more recent studies were not evaluated. Another more recent review by Da-Silva and colleagues (Da-Silva, Moore, & Price, 2018) examined the literature on self-directed home-based upper limb interventions for the stroke population. This study discovered that the most effective home-based self-directed interventions are constraint-induced therapy, electrical stimulation, and no technology interventions. Nevertheless, this study narrowed its scope to self-directed upper limb rehabilitation in the home setting. Other forms of home-based upper limb intervention have not been explored.

More recent evidence and increased availability of advanced technologies in the home setting might significantly influence the evaluation of the updated evidence of upper limb rehabilitation in the home setting. The objectives of this review were to determine the effects of home-based upper limb interventions on improving hemiparetic upper limb function when compared to conventional therapy, placebo, or no intervention in stroke survivors and to identify the types of home-based interventions with optimal benefits to improve the hemiparetic upper limb function in the stroke survivors. The findings of this review will aid researchers and clinicians by providing valuable insights into the updated evidence of the effects of home-based upper limb intervention in stroke rehabilitation and uncover critical elements for its successful implementation.

2.3 Method

2.3.1 Search strategy

The Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA; 19) statement was used to structure this review. From January 2000 to September 2020, a systematic literature search was conducted in four electronic databases: Cochrane Library,

MEDLINE, CINAHL, and Web of Science. Secondary references of eligible studies were hand-searched for additional relevant studies. The search strategy included four types of keywords: “home-based”, “upper limb*”, “rehabilitation”, and “stroke*”.

2.3.2 Selection criteria

This review followed the PICOS framework (http://www.webcitation.org/77dvNDz2q) for the inclusion of studies. Studies were considered for this review if they satisfied the following criteria:

Population (P): Studies that involved adults (i.e. aged ≥18 years) with all stages of stroke; no restrictions were made concerning the type or localisation of stroke.

Intervention (I): Studies that had one or more groups that received upper limb intervention in the home setting (or at least 80% of treatment carried out at home). Interventions targeted to improve upper limb function are self-directed or therapist-supervised, either technology-assisted or ‘no technology’.

Comparator(s)/Control (C): Studies with a comparison group that received conventional therapy, placebo, or no intervention. Conventional treatment refers to the usual stroke rehabilitation care and interventions delivered in a hospital or clinic setting. If the studies compared two or more types of home-based interventions, the comparison group had to be a different type of intervention.

Outcomes (O): Studies that measured outcomes on motor recovery of the hemiparetic upper limb, such as upper limb impairments, functional performance, and use in daily activities.

Study Design (S): Only randomised controlled trials (RCT) and randomised cross-over studies were included. Available studies published in English and that had a full-length publication were included.

Exclusion criteria of this review included: (1) Qualitative studies, systematic, meta-analysis reviews, study protocols, and duplicates; (2) Studies using non-stroke participants; (3) Studies not published in English; (4) Studies using interventions that did not include upper limb training; (5) Studies whose primary focus was on the reduction of other upper limb impairments, i.e. pain, contractures, spasticity, oedema, and shoulder subluxation, etc.

2.3.3 Quality assessment and data extraction

Two independent reviewers (SFMT, CPF) screened for study eligibility based on titles and abstracts of references retrieved during the searches. The two reviewers (SFMT, CPF) independently reviewed the full text of pre-selected articles and agreed on the final set of articles through discussion. Two reviewers (SFMT, CPF) discussed and assessed the methodological quality of the included studies using the Physiotherapy Evidence Database (Pedro) scale, which is a valid and reliable measure of the methodological quality of randomised controlled trials (Maher, Sherrington, Herbert, Moseley, & Elkins, 2003). Any discrepancies were resolved via discussion with the third reviewer (KNKF). The Pedro scale allows the classification of high- and low-quality trials based on cut-off scores. A score of 6 and above on the Pedro scale was considered “high” quality, scores ranging from 4 to 5 were considered “fair” quality, and any studies with a score below 4 were considered “low” quality (Teo, Fong, Chen, & Chung, 2020). The primary author-extracted data included: (1) Author name; (2) Sample size; (3) Participants’ details (i.e. age, gender, the onset of stroke); (4)

Intervention (i.e. content, dose, and duration); (5) Clinical outcome measures; (6) Results (i.e. means, standard deviations, p-values).

2.3.4 Meta-analysis

A meta-analysis was carried out with the following data from the included studies to form a pooled estimate to report the effects of home-based interventions. Primary and secondary outcome measures that measured upper limb function were identified in each study and considered for the meta-analysis if data on mean scores and standard deviation (SDs) were available. All outcome measures were analysed as continuous data using the means and SDs (Higgins et al., 2019). If the studies reported outcome data as medians and interquartile ranges (IQR), the medians and IQR were converted into means and SDs using the formula developed by Hozo, Djulbegovic & Hozo (2005). Most outcome measures in the included studies had rated improvement by a gain score. If a reduced outcome score indicated improvement (i.e. a decrease in time taken to perform a task), the scale direction was aligned with others by multiplying the score by -1 (Higgins, 2011). For studies with a cross-over design, only the first phase data (before cross-over) were included in the analysis to prevent any possibility of learning or carryover effects that would contaminate the data (Da-Silva et al., 2018). The mean change from baseline was used to compare control and intervention groups (Higgins, 2011). For studies that did not report the mean change score and SD but provided pre and post/follow-up scores, the software Open Meta-Analyst (Wallace et al., 2012) was used to calculate the mean change scores. A pooled estimate of the mean differences (MD) with 95% confidence (CI) was calculated if the studies used the same outcome measure.

Regarding studies that used different outcome measures deemed comparable, a standardised mean difference (SMD) with 95% CI was calculated (Higgins et al., 2019).

Publication bias was evaluated graphically using funnel plots (Yang et al., 2019). Egger's linear regression test (Egger, Smith, Schneider, & Minder, 1997) was used for analysis involving five studies and above to assess publication bias in the funnel plot (Bai, Fong, Zhang, Chan, & Ting, 2020).

The heterogeneity of the selected studies was assessed using I^2 statistic; if I^2 was greater than 50% with a significant *p-value*<0.1, the studies were considered heterogeneous (Higgins et al., 2019), and a random model effect was used. A fixed model effect was used to pool study results with low heterogeneity with I^2 less than or equal to 50% (Coupar et al., 2012). In the case of high heterogeneity and significant publication bias, a sensitivity analysis was conducted on the included studies to confirm these effects after adjusting the included data (Higgins et al., 2019; Yang et al., 2019). Procedures related to data pooling in the meta-analysis were carried out in Review Manager 5.3 ("Review Manager (RevMan)," 2014). Comprehensive Meta-analysis 3.0 software (Borenstein, Hedges, Higgins, & Rothstein, 2021) was used for the analysis of publication bias (i.e. Egger regression test).

2.4 Results

2.4.1 Study selection

The PRISMA diagram (Moher, Liberati, Tetzlaff, Altman, & Group, 2009) in Figure 2-1 summarises the literature search results. The initial search from the four databases yielded 943 articles after the removal of 106 duplicates (Cochrane Library n=11; CINAL n=54; MEDLINE n=84; Web of Science n=899, hand search n=1). After screening through the titles and abstracts, 887 articles were excluded. Fifty-six articles were obtained as full texts for

further review by the two reviewers (ST, CPF). Of these articles, twenty-six studies were selected.

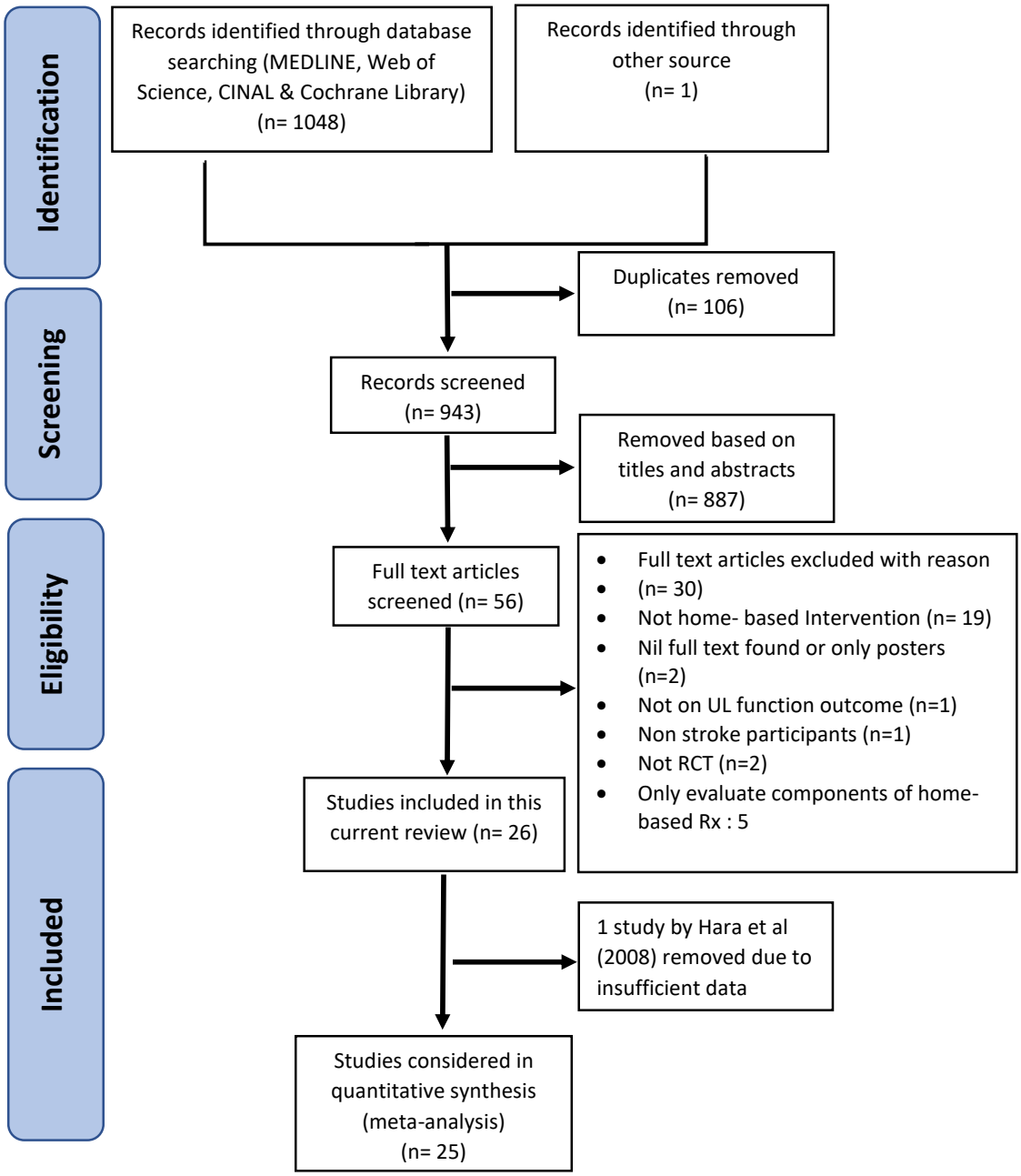
2.4.2 Characteristics of studies and participants

A total of 26 randomized studies were selected. Table 1 provides an overview of the chosen studies, including 21 randomized controlled trials (RCTs) and five randomized crossover trials. All the selected studies were rated as fair to high quality with a mean score of 6.6 ± 1.2 (ranging from 4 to 8) on the Pedro Scale. Table 2 details the individual Pedro score of each study. The total number of participants in this review was 1,428, with the sample size ranging from 12 to 235. The mean age of the participants ranged from 52.3 to 69.4 years. The average time since stroke onset reported in the studies was 23.5 ± 21.2 months. One study (M. Saadatnia et al., 2020) did not report the details of stroke onset in their participants but merely mentioned that their participants were in the acute phase of the stroke.

2.4.3 Types of home-based upper limb interventions

This review included studies that made three types of comparisons: (1) studies that compared the home-based upper limb intervention to conventional therapy conducted in a clinic or hospital (clinic-based therapy), (2) studies that compared the home-based upper limb intervention to no treatment, and (3) studies that compared two different types of home-based interventions.

Figure 2-1: Prisma Diagram



Thirteen studies (Barzel et al., 2015; Choudhury et al., 2020; Cramer et al., 2019; Duncan et al., 2003; Hara, Ogawa, Tsujiuchi, & Muraoka, 2008; Hsieh et al., 2018; Piron et al., 2009; Saadatnia et al., 2020; Standen et al., 2017; Street et al., 2018; Tariah et al., 2010; Turton et al., 2013; Wei et al., 2019) compared home-based intervention to either clinic based therapy or no intervention. Among these studies, 11 (Barzel et al., 2015; Choudhury et al., 2020;. Cramer et al., 2019; Duncan et al., 2003; Hara et al., 2008; Hsieh et al., 2018; Piron et al., 2009; Saadatnia et al., 2020; Tariah et al., 2010; Turton et al., 2013; Wei et al., 2019) used a control group that had undergone clinic-based therapy, and two (Standen et al., 2017; Street et al., 2018) had control groups that did not receive any treatment.

The remaining 13 (Adie et al., 2017; Ballester, Nirme, Camacho, Duarte, Rodriguez, et al., 2017; dos Santos-Fontes, de Andrade, Sterr, & Conforto, 2013; Emmerson, Harding, & Taylor, 2017; Kimberley et al., 2004; Michielsen et al., 2011; Mortensen, Figlewski, & Andersen, 2016; Nijenhuis, Prange-Lasonder, Stienen, Rietman, & Buurke, 2017; Stinear, Barber, Coxon, Fleming, & Byblow, 2008; Sullivan, Hurley, & Hedman, 2012b; Wolf et al., 2015; Zondervan et al., 2015; Zondervan et al., 2016) studies compared two types of home-based interventions. Of which, 10 studies (Adie et al., 2017; Ballester, Nirme, Camacho, Duarte, Rodriguez, et al., 2017; dos Santos-Fontes et al., 2013; Emmerson et al., 2017; Kimberley et al., 2004; Mortensen et al., 2016; Nijenhuis et al., 2017; Sullivan et al., 2012b; Wolf et al., 2015; Zondervan et al., 2016) compared technology-assisted home-based upper limb intervention to “no technology” interventions, while another three studies compared two kinds of “no technology” home-based interventions (Michielsen et al., 2011; Stinear et al., 2008; Zondervan et al., 2015).

Table 2-1: Characteristics of included studies

Study	n (E/C)	Age (yr)	Time since stroke	Primary Outcome measures	Experimental	Control	Therapy dose	Results
Adie et al. 2017	117/118	E: 66.8 ± 14.6 C: 68 ± 11.9	E: 57.3 ± 48.3 (d) C: 56.3 ± 50.1 (d)	ARAT	Home-based Wii grp	Home exercise handout	45min of intervention, daily for 6wks.	No between grp difference (MD: −1.7, 95% CI −3.9–0.5, p = 0.12) on ARAT score to improve UL function
Ballester et al. 2017	17/18	E: 65.1 ± 10.3 C: 61.8 ± 12.9	E: 1073.4 ± 767.7(d) C: 798.1 ± 421.8(d)	FM, CAHAI	Home-based VR	home-based OT	E: 26min 40s of intervention, 1-3 times/d, 5d/wk, 3wks. C: 20min of intervention, 1-3 times/d, 5d/wk, 3wks.	VR was more effective to improve UL function measured by CAHAI scale [1.53 (2.4), p = 0.01] than home-based OT
Barzel et al. 2015	85/71	E: 62.6 ± 13.7 C: 65.3 ± 13.7	E: 56.6 ± 47.4 (mo) C: 45.7 ± 57.7 (mo)	MAL WFMT	Home-based CIMT	NDT clinic-based	E: 50-60min, 5 times/5wks + 40h in 20d of self-practice. C: 25-30min, 10 times/5wks or 50-60min, 5 times/5wks.	Home-based CIMT grp improved more in MAL scores (MD: 0.26, 95% CI 0.05–0.46, p = 0.016) than NDT grp
Choudhurry et al. 2020	32/32	E: 51 ± 12.1 C1: 53 ± 9.9 C2: 53.0 ± 10.6	E: 55 ± 142 (mo) C1: 43 ± 94 (mo) C2: 30 ± 29 (mo)	ARAT, MA S, power and pinch strength, maximum force at wrist joint	Paired stim	C1: Random stim C2: Usual care	4h/d over 4wks.	Paired stim grp improved more ARAT (median baseline: 7.5, week 8: 11.5, p = 0.019) than the other two trainings
Cramer et al. 2019	62/62	E: 62 ± 14 C: 60 ± 13	E: 132 ± 65 (d) C: 129 ± 59 (d)	FM	Home-based telerehab	Outpatient	18 supervised and 18 unsupervised 70min sessions, over 4wks.; 5min/d x 3 times of stroke education.	No between grp difference on FM score (0.06, 95% CI −2.14–2.26, p = 0.96) was found

(Continued)

Table 2-1: (Continued)

Study	n (E/C)	Age (yr)	Time since stroke	Primary Outcome measures	Experimental	Control	Therapy dose	Results
dos Santos-Fontes et al. 2013	10/10	E: 52.2 ± 11.1 C: 59.1 ± 11.1	E: 3.8 ± 4.5 (yr) C: 3.3 ± 2.1 (yr)	Compliance rate to training	Home-based Repetitive peripheral sensory stim	Sham	2h of stimulation daily before motor training, over 4wks. Motor training using the tasks of JTT, 5 out of 7 tasks for 15min, 2 times/d in 4wks at home.	Electrical stim grp improved more in JTT performance than sham grp (14.3%, CI = 1.06–25.6%)
Duncan et al. 2003	50/50	E: 68.5 ± 9 C: 70.2 ± 11.4	E: 77.5 ± 28.7 (d) C: 73.5 ± 27.1 (d)	OPS, FM, Grip strength, WMFT	Home-based therapeutic exercise	Usual care	E: 36 sessions, 90min over 12-14wks. C: not specific	The overall effect of therapeutic exercise had greater gain than usual care (Wilk's l = 0.64, p = 0.0056)
Emmerson, Harding, Taylor 2017	30/32	E: 68 ± 15 C: 63 ± 18	E: 122 (77-193; d, median) C: 133 (58-228; d, median)	Adherence- % of HEP completed.	Home-based iPad grp	Home exercise handout	1-2 times/d with no of exercises varied per d, for 4 wks.	No between grp difference (MD: 0.02s, 95% CI −0.1–0.1) on WMFT log-transformed time to improve UL function
Hara et al. 2008	10/10	E: 56 C: 60.5	E: 13 (mo) C: 13 (mo)	SIAS, ROM, MAS, 10-CMT & 9-HPT	Home-based FES grp	Outpatient	E: 30min, 5d/wk for first 10days, stimulation time 1h/session, 5d/wk for 5mths. C:40min, once/wk for 5mths.	Home-based FES was more effective to improve UL function than outpatient rehab (10-CMT: F = 18.72, p < 0.01)
Hsieh et al. 2018	12/12	E: 53.2 ± 19.2 C: 56.4 ± 18	E: 15.9 ± 13 (mo) C: 13.7 ± 11 (mo)	FM, BBT, Revised NSA, MAL, 10meter walk, sit-to-stand test, COPM, EuroQoL-5D.	Home-based mirror therapy	Mirror therapy in clinic	75-105min, for 12 sessions over 4wks.	Home-based MT grp improved more than clinic MT on MAL (p = 0.01)

(Continued)

Table 2-1: (Continued)

Study	n (E/C)	Age (yr)	Time since stroke	Primary Outcome measures	Experimental	Control	Therapy dose	Results
Kimberly et al. 2004	8/8	E: 58.4 C: 62.8	E: 24.6 (mo) C: 38.5 (mo)	Grip strength, BBT, MAL, JTT, Isometric finger extension strength	Home-based NMES	Sham	3-6h, for 10d over 3wks.	Home-based NMES improved arm function more than sham [BBT: $t(7) = 2.06$, $p = 0.039$; JTT: $t(7) = 3.82$, $p = 0.003$; MAL-AOU: $t(7) = 7.6$, $p < 0.001$; MAL-QOM: $t(7) = 3.82$, $p = 0.003$]
Mortenson et al. 2016	8/8	E: 65.5 C: 60.8	E: 32 (mo) C: 28.8 (mo)	JTT, grip strength	Home-based transcranial stimulation	home-based conventional therapy	30min per session, 5times	Both groups improved in JTT over time ($p < 0.01$). Anodal grp improved more in grip strength than sham ($p = 0.025$)
Michielsen et al. 2011	20/20	E: 55.3 ± 12 C: 58.7 ± 13.5	E: 4.7 ± 3.6 (yr) C: 4.5 ± 2.6 (yr)	FM, Grip strength, Tardieu scale, VAS, ARAT, ABILHAND, Stroke-ULAM, EQ-5D	Home-based mirror therapy	Home- based Bilateral UL training	1hr per session, 5 times/wk at home, 1 time/wk at centre over 6wks.	MT grp improved more in FM than bilateral training grp after Rx (3.6 ± 1.5, $p < 0.05$)
Nijenhuis et al. 2017	9/10	E: 58 (48-65) C: 62 (54-70)	E: 11(10-26; mo) C: 12 (10-30; mo)	IMI, FM, grip strength, MAL, ARAT, BBT, SIS	Home-based robotic	conventional home exercise	30min per session, 5 times/wk over 6wks at home.	CT grp reported higher training duration (189 vs. 118min per wk, $p = 0.025$). No between groups difference in UL outcomes ($p \geq 0.165$)
Piron et al. 2009	18/18	E: 66.0 ± 7.9 C: 64.4 ± 7.9	E: 14.7 ± 6.6 C: 11.9 ± 3.7	FM, ABILHAND scale, Ashworth scale	Home-based telerehab	outpatient	1h per session, 5 times/wk over 4wks at home.	Telerehab grp improved more in FM (53.6 ± 7.7) than clinic (49.5 ± 4.8), $p < 0.05$

(Continued)

Table 2-1: (Continued)

Study	n (E/C)	Age (yr)	Time since stroke	Primary Outcome measures	Experimental	Control	Therapy dose	Results
Saadatnia et al. 2020	20/20	E: 62 ± 12.4 C: 66 ± 10.3	Nil data	BI, FM, MRS	Home-based video exercise	Usual care (in clinic)	E: 1h per session, 2 times/d, daily over 12wks at home + usual care C: usual care as on prescription	Video exercise grp improved more in BI, FM, and MRS score than usual care grp ($p < 0.001$)
Standen et al. 2017	17/10	E: 59 ± 12 C: 63 ± 12	E: 22 (16, 59.5; mo) C: 12 (7.75, 20.25; mo)	WMFT, 9-HPT, MAL, Nottingham Extended activities of daily living	Home-based Nintendo virtual reality	No treatment	E: 20min per session, 3 times/wk over 8wks C: nil	VR grp improved more than control grp in WMFT (r = 0.51, p < 0.05) at midpoint and MAL-AOU (r = 2.26, p < 0.05) at final point
Street et al. 2018	6/6	E: 53.2 ± 21.9 C: 67.6 ± 18.3	E: 19 (mo) C: 13.8 (mo)	ARAT, 9-HPT	Home-based therapeutic instrumental music performance (TIMP)	No treatment	E: 20-30min per session, 2 times/wk over 6wks. C: nil	No between grp difference in overall ARAT score 1.313 (SE:0.674, 95%CI: −0.073–2.698) and 9-HPT 0.169 (SE:0.823, 95%CI: −1.53–1.87)
Stinear et al. 2008	16/16	E: 57.9 (38-78) C: 52.6 (25-73)	E: 28.8 (6-144; mo) C: 20.3 (6-73; mo)	FM, NIHSS, grip strength	Home-based Active passive bilateral training (APBT)	self-directed task training	10-15min per session, 3 times/wk over 4wks	APBT grp improved more UL function ($p < 0.025$) than control grp
Sullivan et al. 2012	20/18	E: 61.6 ± SD (37-88) C: 59.5 ± SD (41-85)	E: 7.7 ± SD (1-29; yr) C: 6.6 ± SD (3-14; yr)	FM, AMAT	Home-based sensory electrical stimulation (SES)	Sham	30min, 2 times/d, 5d/wk over 4wks.	No between grp differences but SES grp improved more on AMAT median time (p = 0.003, 95% CI:−1.4304, −6.365, effect size: 0.84) after Rx

(Continued)

Table 2-1: (Continued)

Study	n (E/C)	Age (yr)	Time since stroke	Primary Outcome measures	Experimental	Control	Therapy dose	Results
Tariah et al. 2010	10/8	E: 54.8 ± 10.9 C: 60.6 ± 4.9	E: 9.2 ± 5.8 C: 9.6 ± 4	WMFT	Home-based CIMT	outpatient NDT	2h/d, 7d/wk over 8wks	CIMT grp improved more in WMFT-FAS [$F(1,15) = 12.68$, $p = 0.003$] as compared to NDT grp
Turton et al. 2017	24/23	E: 66 (54.3, 75.1; mean; IQR) C: 66.1 (57.6, 76.5; mean; IQR)	E: (median, IQR): 111.5 (d) C: median, IQR): 135 (d)	ARAT, WMFT	Home-based Reach-to-Grasp (RTG)	usual care	E:14 visits, 1h/visit over 6 weeks + 56h of self-practice C: not specific	RTG grp improved 6 points for median score of ARAT after Rx but not the usual care grp
Wei et al. 2019	32/25/27	E: 59.2 ± 11.3 C1: 60.4 ± 10.4 C2: 63.1 ± 10.3	E: 47.8 ± 21.9 (d) C1: 61.1 ± 41.3 (d) C2: 53.7 ± 41.2 (d)	FM, ARAT, BBT	Home-based wearable device	C1: sham C2: usual care	E & C1: 3h/d,7d/wk over 4wks C2: not specific	Wearable grp improved more in ARAT score than sham (MD = 6.283, 95% CI 0.812–11.752, $p = 0.019$) and control (MD = 5.767, 95% CI 0.299–11.235, $p= 0.035$)
Wolf et al. 2015	51/48	E: 59.1 ± 14.1 C: 54.7 ± 12.2	E: 115.5 ± 53.1 (d) C: 127.1 ± 46.2 (d)	ARAT	Home-based robotic	Home exercise handout	3h/d, 5d/wk over 8wks	Control group improved more in WMFT than robotic grp ($p =0.012$)
Zondervan et al. 2015	8/8	E: 61 ± 17 C: 54 ± 14	E: 39 ± 46 (mo) C: 24 ± 8 (mo)	FM	Home-based Resonating arm exercise (RAE)	Conventional therapy	3h/3 sessions/wk over 3wks.	Both groups improved in FM ($p < 0.05$) after Rx. RAE grp improved more in distal FM than CT ($p = 0.02$)
Zondervan et al. 2016	9/8	E: 60 (45-74) C: 59 (35-74)	E: 5.33 ± 4.14 (y) C: 3.17 ± 1.66 (y)	BBT, ARAT, MAL & 9-hole peg test	Home-based music glove (VR)	Home-based task-specific training	3h/wk over at least 3 sessions/wk for 3wks.	No between grp difference in ARAT. VR grp improved more in both subscales of MAL ($p = 0.007$, $p = 0.04$)

Note: AMAT: Arm Motor Ability Test; ARAT: Action Research Arm Test; BI: Barthel Index; BBT: Box and Block test; C: control; COPM: Canadian Occupational Performance Measure; CAHAI: Chedoke Arm and Hand Inventory; E: experiment; EQ5D-3L; d: days; FIM: Functional Independence Measure; FM: Fugl Meyer; h: hours HEP: home exercise programme; IMI: Intrinsic Motivation Inventory; JTT: Jebsen Taylor Test; MAL: Motor Activity Log; mo: months; MMT: Manual Muscle testing; MRS: Modified Rankin Scale; NIHSS: National Institute of Health Stroke Scale; 9HPT: Nine hole Peg Test; OPS: Orpington Prognostic Scale; RNSA: Revised Nottingham Sensory Assessment; RCT: randomised controlled trial; Rx: treatment; SIS: Stroke Impact Scale; SIAS: Stroke Impairment Assessment Scale; TEMPA: The Upper Extremity Performance Test; 10-CMT: ten-cup-moving test; VAS: Visual Analogue Scale for Pain; WMFT: Wolf motor function test; wk: weeks; yr: years

Table 2-2: Methodological quality of studies

Studies	**Pedro scale**												
	1	2	3	4	5	6	7	8	9	10	11	Total	Type
Adie et al. (34)	Yes	1	1	1	0	0	1	1	1	1	1	8	H
Ballaster et al. (35)	Yes	1	0	1	0	0	0	1	0	1	1	5	F
Barzel et al. (36)	Yes	1	1	1	0	0	1	1	1	1	1	8	H
Choudhury et al. (37)	Yes	1	1	1	0	0	1	1	1	1	1	8	H
Dos-Sanrtose-fontes et al. (39)	Yes	1	1	1	0	0	1	1	1	1	1	8	H
Duncan et al. (17)	Yes	1	1	1	0	0	1	1	1	1	1	8	H
Emmerson et al. (40)	Yes	1	1	1	0	0	1	1	0	1	1	7	H
Hara et al. (41)	Yes	1	0	0	0	0	1	1	0	1	1	5	F
Hsieh et al. (18)	Yes	1	0	1	0	0	1	0	0	1	1	5	F
Kimberly et al. (42)	Yes	1	0	1	1	0	1	1	0	0	1	6	H
Michielsen et al. (44)	Yes	1	1	1	0	0	1	1	1	1	1	8	H
Mortensen at al. (43)	Yes	1	1	1	1	0	1	1	0	1	1	8	H
Nijenhuis et al. (45)	Yes	1	1	1	0	0	0	1	0	1	1	6	H
Prion et al. (46)	No	1	1	1	0	0	1	1	0	1	1	7	H
Saadatnia et al. (9)	Yes	1	0	1	0	0	0	0	0	1	1	5	F
Standen et al. (47)	No	1	1	1	0	0	1	0	0	1	1	6	H
Stinear et al. (49)	Yes	1	0	1	0	0	1	0	0	1	1	5	F
Street et al. (48)	Yes	1	0	1	0	0	1	1	0	1	1	6	H
Sullivan et al. (50)	Yes	1	0	1	0	0	1	1	1	1	1	7	H
Tariah et al. (51)	Yes	1	0	1	0	0	1	1	0	1	1	6	H
Turton et al. (52)	Yes	1	1	1	0	0	1	1	1	0	1	7	H
Wei et al. (8)	Yes	1	0	1	0	0	1	1	1	1	1	7	H
Wolf et al. (53)	Yes	1	0	1	0	0	1	1	1	1	1	7	H
Zondervan et al. (54)	Yes	0	0	1	0	0	1	1	1	1	1	6	H
Zondervan et al. (55)	Yes	1	0	1	0	0	1	1	0	1	1	6	H

1: eligibility criteria; 2: random allocation; 3: concealed allocation; 4: baseline comparability; 5: blind participants; 6: blind therapist; 7: blind assessor; 8: adequate follow-up; 9: intention to treat; 10: between group comparison; 11: point estimate variability. Quality: High Quality (H), Fair Quality (F), Low Quality (L).

Eighteen studies (Adie et al., 2017; Ballester et al., 2017; Choudhury et al., 2020; Cramer et al., 2019; dos Santos-Fontes et al., 2013; Emmerson et al., 2017; Hara et al., 2008; Kimberley et al., 2004; Mortensen et al., 2016; Nijenhuis et al., 2017; Piron et al., 2009; Saadatnia et al., 2020; Standen et al., 2017; Street et al., 2018; Sullivan et al., 2012; Wei et al., 2019; Wolf et al., 2015; Zondervan et al., 2016) used technology-assisted home-based upper limb interventions in their experimental groups to examine the treatment effects on hemiplegic upper limb recovery. In these studies, the technology-assisted interventions used were interactive video games (on devices such as Wii, iPad, Kinect), virtual reality, electrical stimulation (including transcranial stimulation), robotics, telerehabilitation, and wearable devices. Most of these 18 studies (n = 15) adopted either self-directed or remote supervision by a therapist in delivering the interventions (Adie et al., 2017; Ballester et al., 2017; Choudhury et al., 2020; Cramer et al., 2019; dos Santos-Fontes et al., 2013; Emmerson et al., 2017; Hara et al., 2008; Kimberley et al., 2004; Nijenhuis et al., 2017; Piron et al., 2009; Standen et al., 2017; Sullivan et al., 2012; Wei et al., 2019; Wolf et al., 2015; Zondervan et al., 2016). Three studies (Mortensen et al., 2016; Saadatnia et al., 2020; Street et al., 2018) used direct supervision or a hybrid model. Table 3 presents the types of home-based upper limb interventions and the mode of delivery.

The remaining eight studies (Barzel et al., 2015; Duncan et al., 2003; Hsieh et al., 2018; Michielsen et al., 2011; Tariah et al., 2010; Turton et al., 2013; Zondervan et al., 2015) used "no technology" interventions in the home setting. These interventions included home-based constraint-induced movement therapy (HOME-CIMT), task-specific training, therapeutic exercise, mirror therapy (MT), and mechanical device training. The HOME-CIMT used in the two included studies (Barzel et al., 2015; Tariah et al., 2010) was different fromthe traditional CIMT in which all training was conducted solely at the participants' homes and not in the clinic. Three-quarters of these "no" technology home-based interventions (Barzel et al., 2015; Duncan

et al., 2003; Hsieh et al., 2018; Michielsen et al., 2011; Tariah et al., 2010; Turton et al., 2013) involved direct contact with the therapists, with only two studies using a self directed mode (Stinear et al., 2008; Zondervan et al., 2015).

2.4.4 Outcome Measures

This review primarily focused on outcomes for the upper limb motor and functional use. The outcome measures varied across the studies. Eighteen studies (Ballester et al., 2017; Choudhury et al., 2020; Cramer et al., 2019; Duncan et al., 2003; Hara et al., 2008; Hsieh et al., 2018; Kimberley et al., 2004; Michielsen et al., 2011; Mortensen et al., 2016; Nijenhuis et al., 2017; Piron et al., 2009; Saadatnia et al., 2020; Stinear et al., 2008; Sullivan et al., 2012; Tariah et al., 2010; Wei et al., 2019; Weiss, Kizony, Feintuch, & Katz, 2006; Zondervan et al., 2015) used outcome measures that measured upper limb impairments. The most popular outcome measures used were the Fugl-Meyer Assessment-Upper Extremity subscore (FMA-UE) (n=14), followed by grip strength (n=8) and ROM(n=2). Twenty-three studies (Adie et al., 2017; Ballester et al., 2017; Barzel et al., 2015; Choudhury et al., 2020; Cramer et al., 2019; dos Santos-Fontes et al., 2013; Duncan et al., 2003; Emmerson et al., 2017; Hara et al., 2008; Hsieh et al., 2018; Kimberley et al., 2004; Michielsen et al., 2011; Mortensen et al., 2016; Nijenhuis et al., 2017; Standen et al., 2017; Street et al., 2018; Sullivan et al., 2012; Tariah et al., 2010; Turton et al., 2013; Wei et al., 2019; Wolf et al., 2015; Zondervan et al., 2015; Zondervan et al., 2016) measured intervention effects using outcome measures that assessed arm function. The commonly reported outcome measures were the Action Research Arm Test (ARAT; n=9),Wolf Motor Function Test (WMFT; n = 7), Box and Block Test (BBT; n = 7), Nine-hole Peg Test (9-HPT; n = 5), and Jebsen–Taylor Test (JTT; n = 3).

This review considered the participant's perception of the affected arm use in daily activities as one of the focused outcomes. Though it is commonly assumed that improvements in the upper limb capacity as measured by standardized upper limb assessments would translate into improved use of the affected arm in daily activities, Waddell et al. (2017) highlighted that this is not the case. Eleven studies (Barzel et al., 2015; Hsieh et al., 2018; Kimberley et al., 2004; Nijenhuis et al., 2017; Standen et al., 2017; Sullivan et al., 2012; Tariah et al., 2010; Turton et al., 2013; Wei et al., 2019; Zondervan et al., 2015; Zondervan et al., 2016) used the Motor Activity Log (MAL) to assess the participant's perception of the affected arm. The MAL is a self-reported questionnaire to assess how often and well the patients used their affected arm daily (Uswatte, Taub, Morris, Light, & Thompson, 2006). It consisted of two subscales: the amount of use (MAL-AOU) and quality of movement (MAL-QOM) of the paretic arm.

2.4.5 Effects of interventions

A meta-analysis was conducted to examine the clinical effects of home-based upper limb interventions. This review included three categories of studies: (1) studies that compared the home-based upper limb interventions to clinic-based therapy, (2) studies that compared two forms of home-based upper limb interventions (technology-assisted and "no technology"), and (3) studies that compared home-based upper limb interventions to no intervention. To address the review's objectives, comparisons were made on the effects of the studies in these three categories.

Table 2-3: Types of interventions and mode of delivery

Comparison 1: Home-based UL therapy to clinic-based therapy			
Studies	**Types of 'experiment' intervention**	**Classification of 'experimented' intervention**	**Mode of delivery**
Barzel et al. (34)	Home-CIMT	'No' tech	Exp grp: Hybrid • Self-directed • Direct supervised Con grp: Direct supervised
Choudhury et al. (35)	Electrical stimulation	Tech-assisted	Exp grp: Self-directed Con grp: Direct supervised
Cramer et al. (36)	Telerehabilitation	Tech-assisted	Exp grp: Remote supervised Con grp: Direct supervised
Duncan et al. (17)	Therapeutic exercise	'No' tech	Both grps: Direct supervised
Hara et al. (37)	Electrical stimulation	Tech-assisted	Exp grp: Self-directed Con grp: Direct supervised
Hsieh et al. (18)	Mirror therapy	'No' tech	Both grps: Direct supervised
Piron et al. (38)	Telerehabilitation	Tech-assisted	Exp grp: Remote supervised Con grp: Direct supervised
Saadatnia et al. (9)	Virtual reality	Tech-assisted	Exp grp: Hybrid • Self-directed • Direct supervised Con grp: Direct supervised
Tariah et al. (39)	Home-CIMT	'No' tech	Exp grp: Hybrid • Self-directed • Direct supervised Con grp: Direct supervised
Turton et al. (40)	Task-specific training	'No' tech	Exp grp: Hybrid • Self-directed • Direct supervised Con grp: Direct supervised
Wei et al. (8)	Wearable device training	Tech-assisted	Exp grp: Self-directed Con grp: Direct supervised
Comparison 2: Home-based UL therapy to no intervention			
Studies	**Types of 'experiment' intervention**	**Classification of 'experimented' intervention**	**Mode of delivery**
Standen et al. (41)	Virtual reality	Tech-assisted	Exp grp: Self-directed Con grp: NA
Street et al. (42)	Music therapy	Tech-assisted	Exp grp: Direct supervised Con grp: NA

Table 2-3: Types of interventions and mode of delivery

Comparison 3: Home-based technology to 'no tech' intervention			
Studies	**Types of 'experiment' intervention**	**Classification of 'experimented' intervention**	**Mode of delivery**
Adie et al. (43)	Virtual reality	Tech-assisted'	Both grps: Self-directed
Ballester et al. (44)	Virtual reality	Tech-assisted	Both grps: Self-directed
dos Santos-Fontes et al. (45)	Electrical stimulation	Tech-assisted	Both grps: Self-directed
Emmerson, Harding & Taylor (46)	Virtual reality	Tech-assisted	Exp grp: Remote supervised Con grp: Self-directed
Kimberly et al. (47)	Electrical stimulation	Tech-assisted	Both grps: Self-directed
Mortenson et al. (48)	Electrical stimulation	Tech-assisted	Both grps: Direct supervised
Nijenhuis et al. (49)	Robotics	Tech-assisted	Both grps: Self-directed
Sullivan et al. (51)	Electrical stimulation	Tech-assisted	Both grps: Self-directed
Wolf et al. (52)	Robotics	Tech-assisted	Both grps: Self-directed
Zondervan et al. (53)	Virtual reality	Tech-assisted	Both grps: Self-directed
Comparison 4: Two types of 'no technology' home-based interventions			
Studies	**Types of 'experiment' intervention**	**Classification of 'experimented' intervention**	**Mode of delivery**
Michielsen et al. (54)	Mirror therapy	'No' tech	Both grps: Self-directed
Stinear et al. (50)	Mechanical device	'No' tech	Both grps: Self-directed
Zondervan et al. (55)	Mechanical device	'No' tech	Both grps: Self-directed

Legend: Con: control; Exp: Experiment, grp: group; tech: technology, NA: not applicable

2.4.5.1 Home-based UL intervention vs clinic-based therapy

A pooled meta-analysis (figure 2-2) involving eight studies (Barzel et al., 2015; Choudhury et al., 2020; Cramer et al., 2019; Duncan et al., 2003; Hsieh et al., 2018; Tariah et al., 2010; Turton et al., 2013; Wei, Fong, Chung, Cheung, & Chow, 2019) was carried out to examine the effect of home-based upper limb interventions on the function of the upper limb when compared to clinic-based therapy immediately after treatment and at follow-up. In these eight studies (Barzel et al., 2015; Choudhury et al., 2020; Cramer et al., 2019; Duncan et al., 2003; Hsieh et al., 2018; Tariah et al., 2010; Turton et al., 2013; Wei et al., 2019), three studies used home-based technology-assisted interventions such as electrical stimulation, wearable device, and telerehabilitation (Choudhury et al., 2020; Cramer et al., 2019; Wei et al., 2019), and these interventions were either self-directed or remotely supervised by a therapist. The other five studies (Barzel et al., 2015; Duncan et al., 2003; Hsieh et al., 2018; Tariah et al., 2010; Turton et al., 2013) used "no technology" interventions such as HOME-CIMT, mirror therapy, therapeutic exercises, and goal-oriented task-specific training. All these "no technology" interventions required direct contact with the therapist. A mixture of upper limb outcome measures was used in these eight studies. Three studies (Choudhury et al., 2020; Turton et al., 2013; Wei et al., 2019) used ARAT, another three used WMFT (Barzel et al., 2015; Duncan et al., 2003; Tariah et al., 2010), and two studies used Box and Block Test (Cramer et al., 2019; Hsieh et al., 2018).

The pooled effects from the meta-analysis demonstrated that home-based upper limb intervention improved the hemiplegic upper limb function more significantly than clinic-based therapy [SMD: 0.28, 95% CI (0.12, 0.44), $I^2 = 0\%$, $p < 0.001$, fixed effect model]. The funnel plot showed no publication bias supported by Egger's test (b: 0.04, SE: 1.24, $p = 0.98$). Subgroup analysis revealed that studies that used "no technology" home based interventions contributed to the favorable pooled result. These studies (Barzel et al., 2015; Duncan et al.,

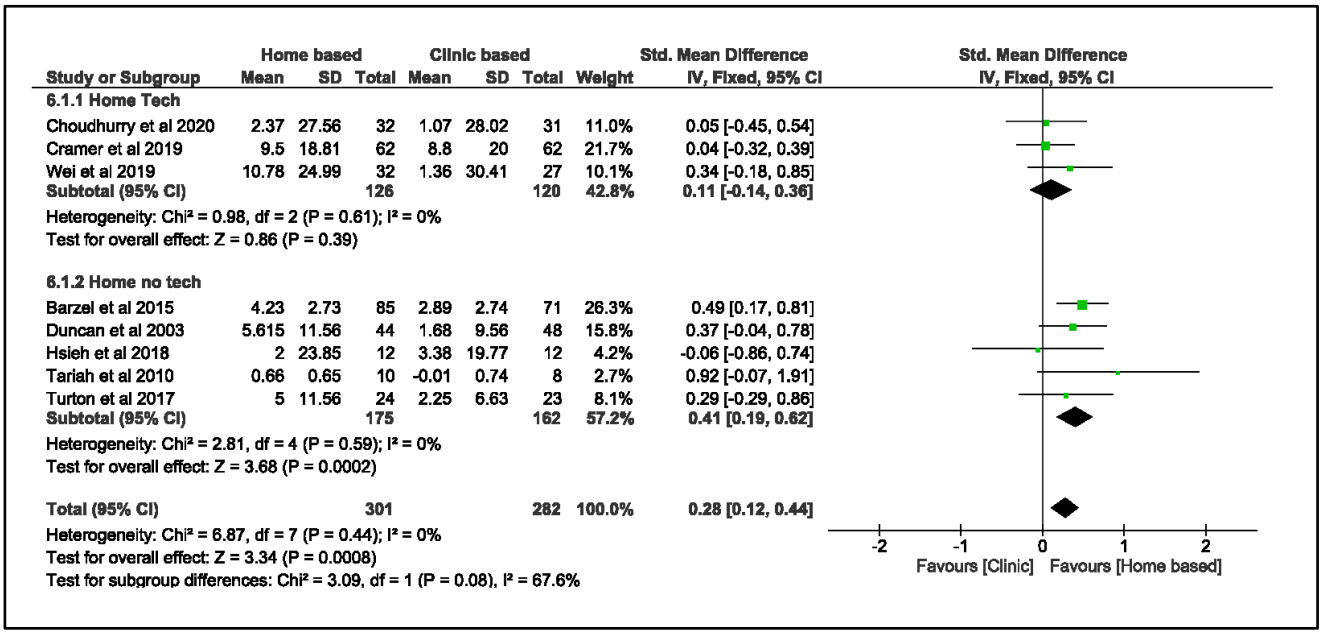
2003; Hsieh et al., 2018; Tariah et al., 2010; Turton et al., 2013) indicated a statistically significant benefit over clinic-based therapy to improve UL function immediately after treatment [SMD: 0.41, 95%CI (0.19, 0.62), I2 = 0%, p < 0.001, fixed effect model]. In contrary, studies that used home-based technology-assisted upper limb intervention (Choudhury et al., 2020; Cramer et al., 2019; Wei et al., 2019) did not show similar effects [SMD: 0.11, 95% CI (−0.14, 0.36), I^2 = 0%, p = 0.39, fixed effect model].

The pooled results from five studies (Barzel et al., 2015; Choudhury et al., 2020; Tariah et al., 2010; Turton et al., 2013; Wei et al., 2019) that measured the effects of home-based upper limb intervention at follow-up demonstrated that the improvements in upper limb function were sustained [SMD: 0.28, 95% CI (0.07, 0.50), I^2 = 0%, p = 0.01, fixed effect model] with no publication bias (Egger's test: b: 1.56, SE: 0.72, p = 0.12). Similarly, further analysis showed that studies (Barzel et al., 2015; Tariah et al., 2010; Turton et al., 2013) that used "no technology" interventions were the main contributor to this effect [SMD: 0.31, 95% CI (0.04, 0.57), I2 = 0%, p = 0.02, fixed effect model].

Besides the improvements in upper limb function, the effects of home-based upper limb interventions on the participants' perceived use of their paretic arm in daily routine were analyzed using the MAL outcomes. Meta-analysis of four studies (Barzel et al., 2015; Hsieh et al., 2018; Tariah et al., 2010; Turton et al., 2013) (Figure 2-3) demonstrated that the home-based intervention group improved more than the clinic-based intervention group in the MAL scores: MAL-AOU [MD: 0.32, 95% CI (0.11, 0.53), I^2 = 0%, p = 0.003, fixed effect model] and MAL-QOM [MD: 0.24, 95% CI (0.05, 0.43), I^2 = 0%, p = 0.01, fixed model]. This positive effect was sustained at follow-up: MAL-AOU [MD: 0.29, 95% CI (0.07, 0.51), I^2 = 0%, p = 0.009, fixed effect model], and MAL-QOM [MD: 0.21, 95% CI (0.03, 0.40), I^2 = 0%, p = 0.03, fixed effect model].

Figure 2- 2: Comparison of the effect of home-based intervention and conventional therapy on UL function (A) immediately after treatment. (B) at follow-up.

(A)



(B)

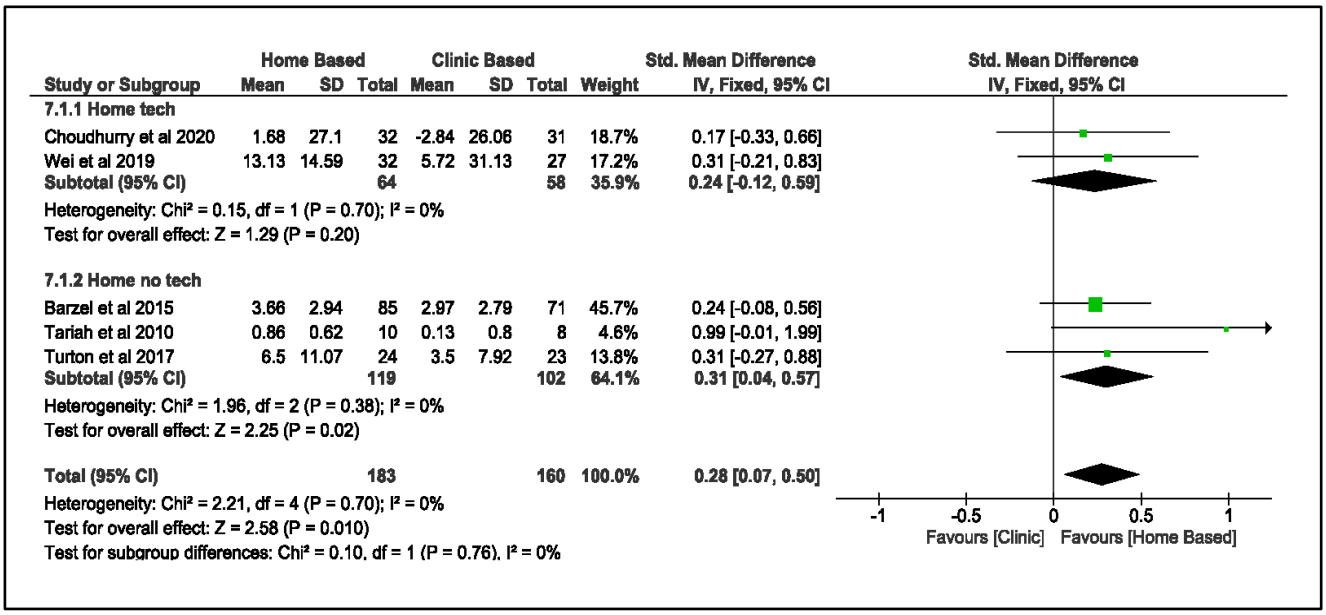
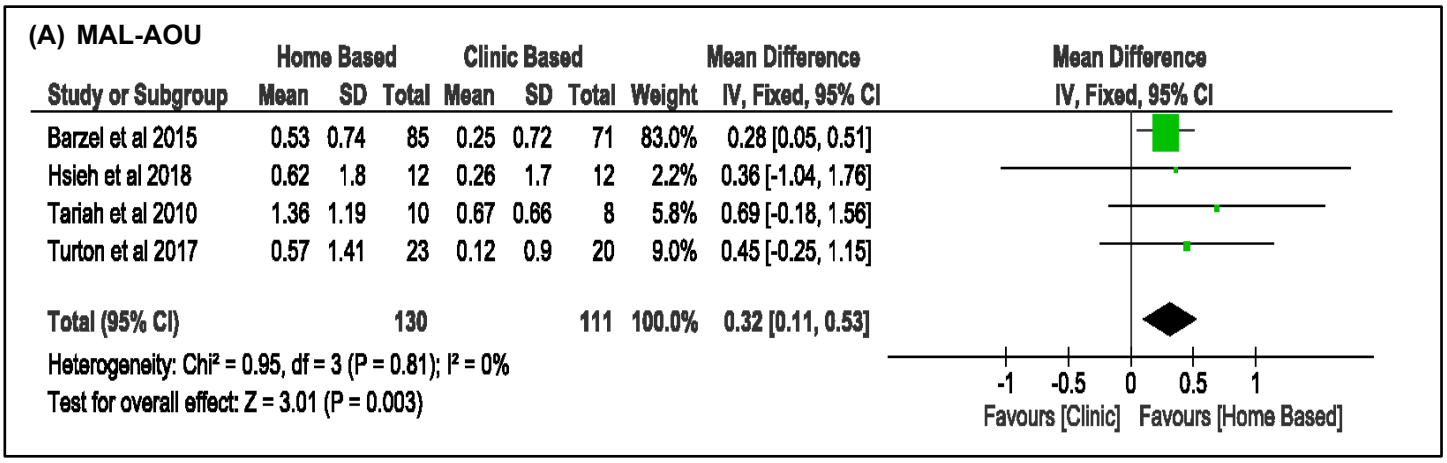


Figure 2-3: Comparison of the effect of home-based intervention and conventional therapy on MAL outcomes (A) immediately after treatment. (B) at follow-up.



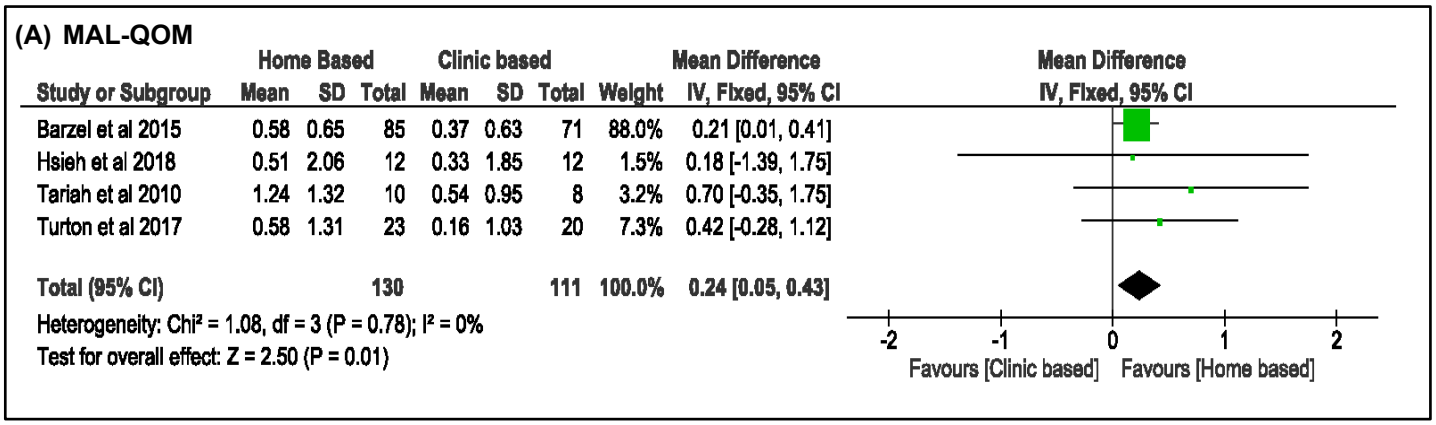
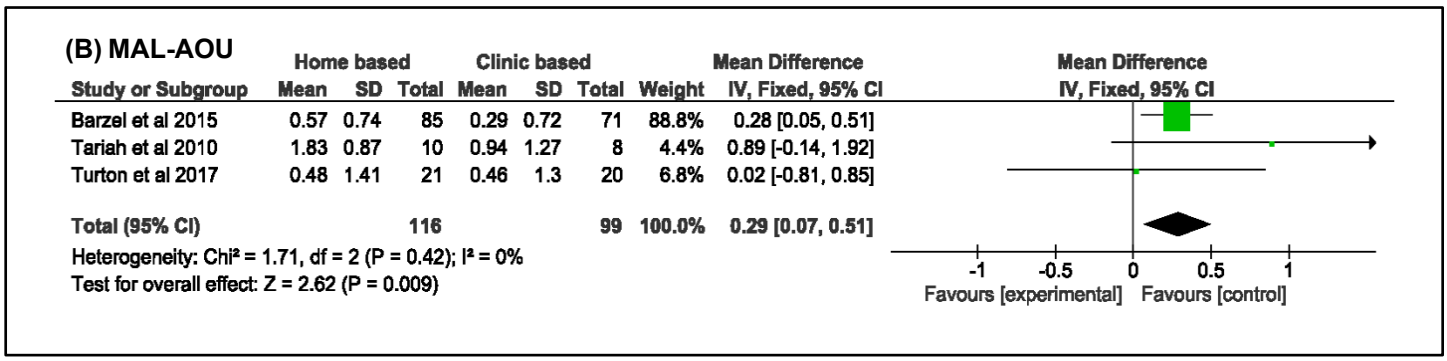
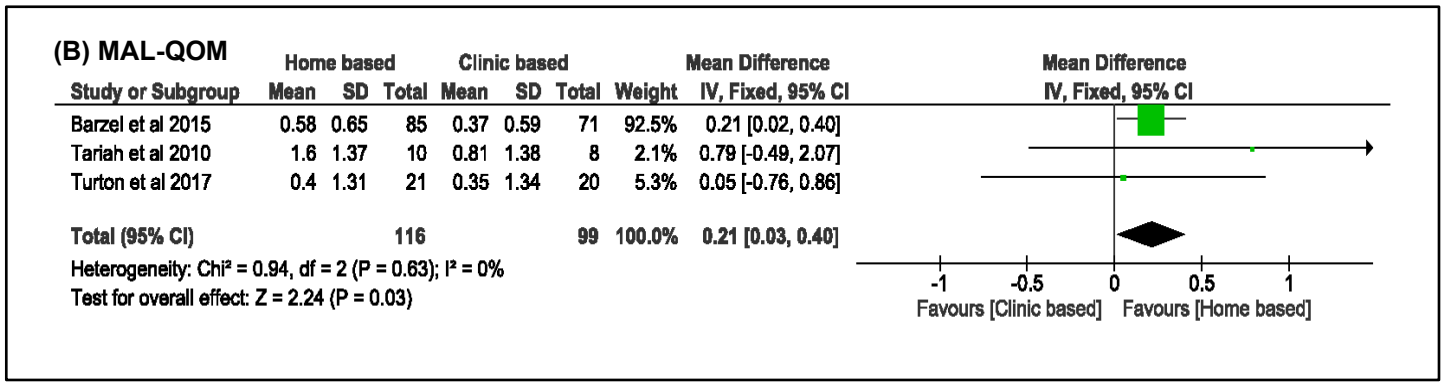


Figure 2-3: Comparison of the effect of home-based intervention and conventional therapy on MAL outcomes (A) mean difference (MD) immediately after treatment. (B) mean difference (MD) at follow-up.





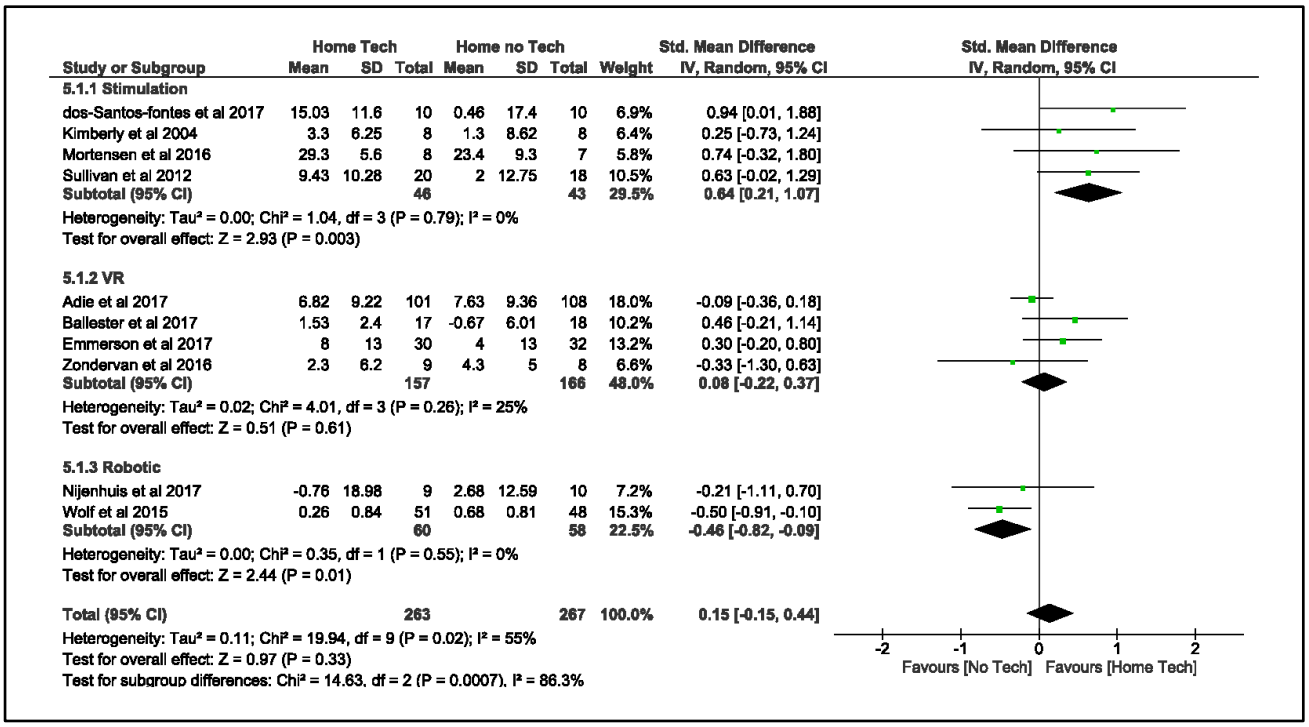
2.4.5.2 Home-based technology-assisted intervention vs "no technology" intervention

A pooled analysis of 10 studies (Adie et al., 2017; Ballester et al., 2017; dos Santos-Fontes, de Andrade, Sterr, & Conforto, 2013; Emmerson, Harding, & Taylor, 2017; Kimberley et al., 2004; Mortensen, Figlewski, & Andersen, 2016; Nijenhuis, Prange-Lasonder, Stienen, Rietman, & Buurke, 2017; Sullivan, Hurley, & Hedman, 2012; Wolf et al., 2015; Zondervan et al., 2016) that compared the effects of technology-assisted home-based interventions on upper limb function to "no technology" home-based interventions was conducted (see Figure 2-4). These studies used three broad categories of technology-assisted interventions: electrical stimulation (including transcranial direct stimulation), virtual reality, and robotics in the experimental groups. All the home-based interventions used in these studies except for one (Mortensen et al., 2016) are either self-directed or remotely supervised by a therapist. The overall effects showed similar improvements in both the technology-assisted home-based intervention groups and their control groups that used "no technology" intervention after treatment [SMD: 0.15, 95% CI (−0.15, 0.44), I^2 = 55%, $p = 0.33$, random effect model] and at follow-up [SMD: −0.02, 95% CI (−0.26, 0.21), I^2 = 12%, $p = 0.85$, fixed effect model]. The funnel plots for both analyses were symmetrical with no publication bias supported by Egger's test (after treatment: b: 1.62, SE: 0.942, $p = 0.125$; follow-up: b: 1.35, SE: 0.67, $p = 0.136$).

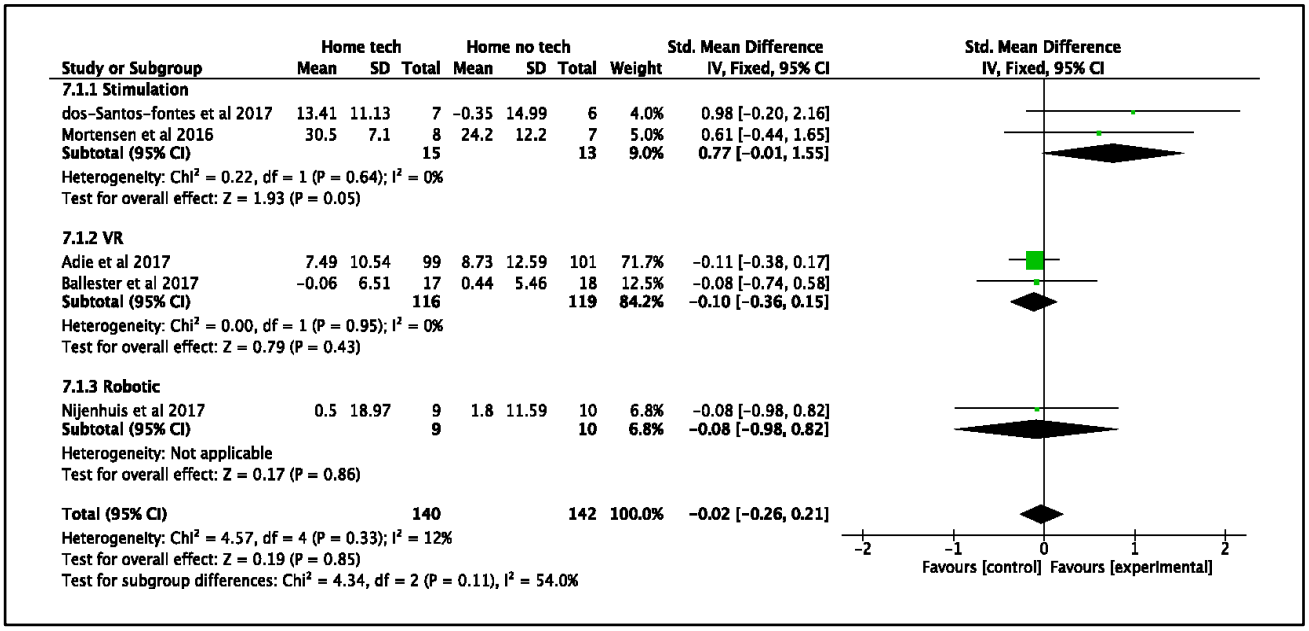
Nevertheless, further subgroup analysis revealed differing results in the three categories of interventions. Interventions that used electrical stimulation (dos Santos-Fontes et al., 2013; Kimberley et al., 2004; Mortensen et al., 2016; Sullivan et al., 2012) demonstrated statistically significant benefits in improving the paretic upper limb function as compared to sham or task-specific training after treatment [SMD: 0.64, 95% CI (0.21, 1.07), I^2 = 0%, $p = 0.003$, random effect model] and at follow-up [SMD: 0.77, 95% CI (−0.01, 1.55), I^2 = 0%, $p = 0.05$, fixed effect model].

Figure 2 -4: Comparison of the effect of technology-assisted home-based intervention and 'no technology' intervention on UL function (A) immediately after treatment. (B) at follow-up.

(A)



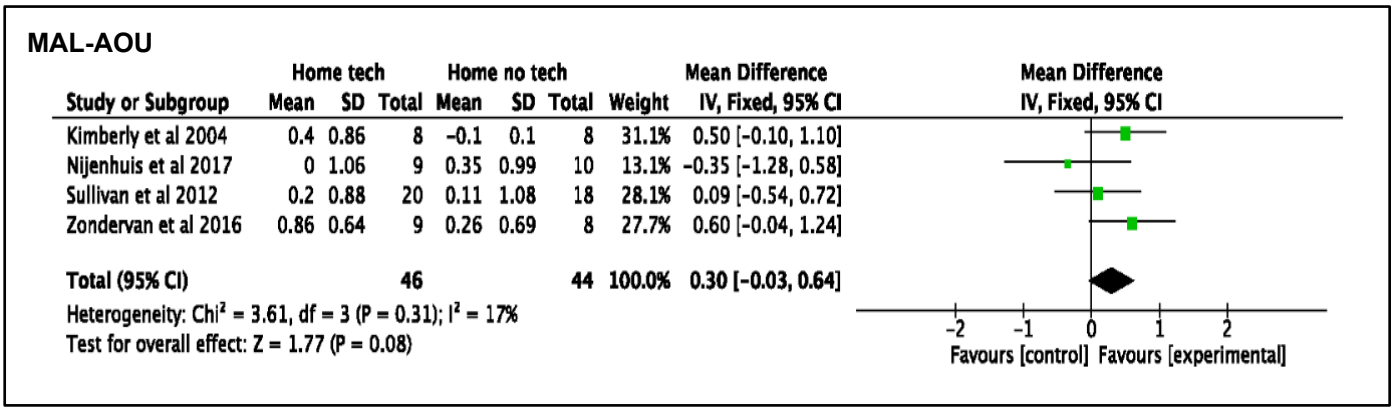
(B)

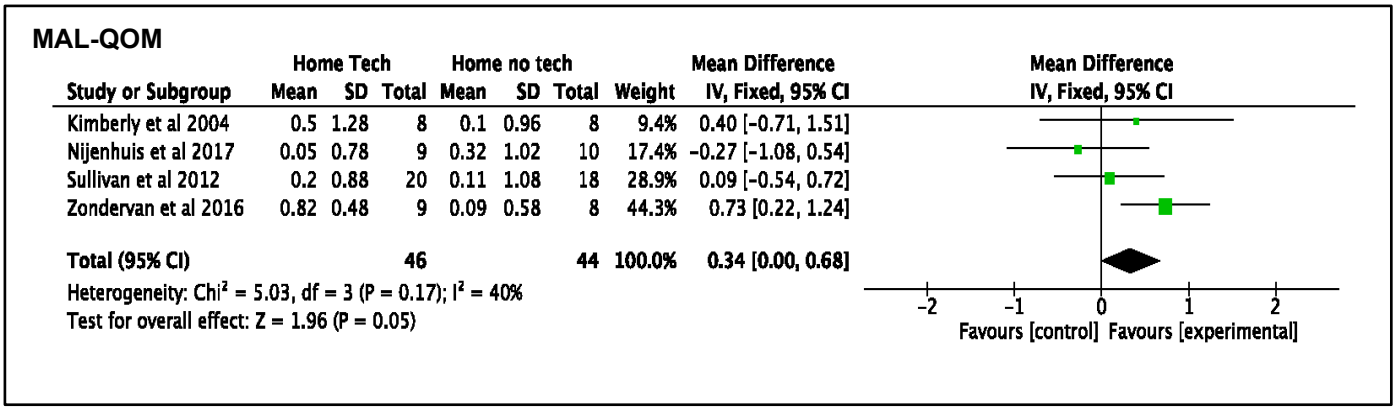


On the contrary, results from robotic studies (Nijenhuis et al., 2017; Wolf et al., 2015) favored their control groups that used the "no technology" home exercises program [SMD: −0.46, 95% CI (−0.82, −0.09), $I^2 = 0\%$, $p = 0.01$, random effect model] after treatment but not at follow-up [SMD:−0.08, 95%CI (−0.98, 0.82), $p=0.86$, fixed effect model]. Results from virtual reality studies (Adie et al., 2017; Ballester et al., 2017; Emmerson et al., 2017; Zondervan et al., 2016) found no group differences between virtual reality and their control groups at the two time points: after treatment (VR: SMD: 0.08, 95% CI (-0.22, 0.37), I^2=25%, $p=0.61$, random effect model) and at follow-up (VR: SMD: 0.10, 95% CI (-0.36, 0.15), I^2=0%, $p=0.43$, fixed effect model.

Regarding the participants' perceived use of their paretic arm in daily activities, the meta-analysis of four studies (Kimberley et al., 2004; Nijenhuis et al., 2017; Sullivan et al., 2012; Zondervan et al., 2016) found different pooled outcomes on the two subscales in MAL when examining the effect of technology-assisted interventions (see Figure 2-5). The technology-assisted interventions had a beneficial effect on the quality of arm movement (MAL-QOM) when compared to "no technology" interventions [MD: 0.34, 95% CI (0, 0.68), $I^2 = 40\%$, $p = 0.05$, fixed effect model]. However, the analysis narrowly failed to show a statistically significant benefit on the amount of use (MAL-AOU) [MD: 0.30, 95% CI (−0.03, 0.64), $I^2 = 17\%$, $p = 0.08$, fixed effect model]. Further analysis found that the work by Zondervan et al. (2016) was the main contributor to the significant result in MAL-QOM. It implied that the observed pooled outcome of technology-assisted home intervention might not be conclusive.

Figure 2 -5: Comparison of the effect of the technology-assisted home-based intervention and 'no technology' intervention on MAL outcomes immediately after treatment MAL-AOU and MAL-QOM.

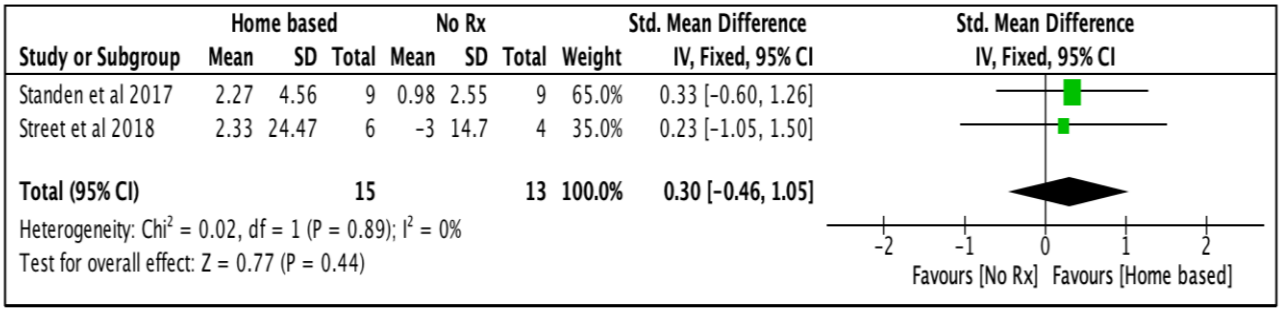




2.4.5.3 Home-based intervention vs no intervention

Two studies (Standen et al., 2017; Street et al., 2018) used no interventions in their control group compared to their technology-assisted home-based upper limb intervention. The pooled effect did not demonstrate a statistically significant benefit of home-based treatment over no treatment to improve UL function [SMD: 0.30, 95% CI (−0.46, 1.05), $I^2 = 0\%$, $p = 0.44$, fixed effect model; Figure 2-6]. A possible reason might be these studies' small effects and sample sizes.

Figure 2- 6: Comparison of the effect of home-based intervention and no treatment on UL function after treatment



2.5 Discussion

This review summarises the methodological qualities, content, and clinical effects of home-based upper limb rehabilitation in stroke rehabilitation. The characteristic of this review is that all the included studies were randomized controlled trials (RCT) and randomized cross-over trials, and the majority were high-quality trials. With clear clinical relevance and focus, the meta-analysis added rigor to the synthesis in evaluating the effectiveness of home-based interventions to improve upper limb function after stroke.

This review examined the effects of home-based upper limb rehabilitation on hemiparetic upper limb motor recovery in stroke survivors. Two key findings were highlighted in the meta-analysis:(1) home-based upper limb interventions were more effective in improving hemiparetic upper limb function and increasing participants' satisfaction in the use of the affected arm in daily activities than clinic-based therapy after treatment and at follow-up; (2) among the home-based interventions, those that used electrical stimulation weremore effective in improving the hemiplegic arm's function than "no technology" intervention after treatment and follow-up.

The pooled evidence demonstrated that the home-based upper limb intervention was superior to clinic-based therapy in improving the hemiplegic arm's function after stroke. This finding is considered new compared to a previous Cochrane review (Coupar, Pollock, Legg, Sackley, & van Vliet, 2012). Due to the paucity of available studies, the review (Coupar et al., 2012) found insufficient evidence (i.e. four RCTs) to determine the effects of home-based therapy programmes for upper limb recovery in stroke survivors. In this review, the upper limb functional gains in participants who received the home-based intervention were consistent with their satisfaction with the affected arm's daily use, as reflected in their motor activity log scores. This consistency between the participant's motor improvement and satisfaction illustrated the

benefits of interventions conducted in the home setting. Previous evidence suggested a possible influence of the home environment on the treatment outcome (Cunningham, Turton, Van Wijck, & Van Vliet, 2016; Dobkin, 2017). Home-based rehabilitation provides contextually dependent learning and uses daily objects that are relevant to the patients (Cunningham et al., 2016; Trombly & Wu, 1999). Patients who practised in a familiar environment were likely to transfer skills learned in real-world activities (Dobkin, 2017). The clinic where conventional therapy was carried out served as a poor surrogate environment separating the person from the natural context (Hillier & Inglis-Jassiem, 2010). Transfer of skills and treatment effects from such an environment to a real-life situation might be inadequate and not feasible (Hillier & Inglis-Jassiem, 2010; Tariah et al., 2010). Waddell et al. (2017) found that upper limb training designed to improve upper limb capacity in the clinic setting was insufficient to translate into actual improvements in upper limb performance in daily activities. One possible reason was that therapists who provide training in the clinic might be unaware of the constraints (or supports) in the person's real-life environment to assist the patients in translating skills (Hillier & Inglis-Jassiem, 2010). Therefore, it is recommended that therapists providing training to the patients outside of the home context should consider the patient's home environment setup.

Despite the overall positive effects of home-based upper limb intervention over conventional therapy, only the effect of 'no technology' interventions was superior to conventional therapy in the clinic when a subgroup analysis was performed. The types of 'no technology' interventions used are task-specific training, therapeutic exercises, and home-based CIMT. All these studies (Barzel et al., 2015; Duncan et al., 2003; Hsieh et al., 2018; Tariah et al., 2010; Turton et al., 2013) involved direct contact with the therapist in their interventions. One possible explanation for the positive effect was that the studies (Barzel et al., 2015; Duncan et al., 2003; Hsieh et al., 2018; Tariah et al., 2010; Turton et al., 2013) had used customised and relevant functional activities that matched the participants' goals and arm

capacity. This method and direct contact with the therapist kept the participants engaged and compliant with the therapy regime, triggering positive results. In an unstructured setting like the home, interventions need relevance and command enough interest to keep patients motivated and engaged (Da-Silva, Moore, & Price, 2018).

On the contrary, our review indicated that the effects of the home-based technology-assisted interventions were similar to clinic-based therapy. To highlight, all these interventions in these studies (Choudhury et al., 2020; Cramer et al., 2019; Wei et al., 2019) were self-directed or remotely supervised by the therapist. One purpose of using home-based technologies was to reduce the need for direct contact with a therapist, ameliorating the saturated health services (Akbari, Haghverd, & Behbahani, 2021). Nonetheless, this observation from the subgroup analysis highlighted critical considerations when choosing the type of technology-assisted home-based upper limb interventions. The use of home-based technologies requires additional consideration of a broader range of factors, such as the individual's motivation, social context, technical proficiency, physical space and the usability and therapeutic design of the technology devices (Adie et al., 2017; Chen et al., 2019). Inadequate consideration of these factors might affect the patient's motivation and adherence to the therapy regime, especially in the absence of the therapist, thereby affecting the treatment outcomes (Chen et al., 2019).

Another key finding was that differential effects were found in different interventions after treatment and follow-up when comparing technology-assisted home-based intervention to 'no technology' home-based intervention in the ten included studies (Adie et al., 2017; Ballester et al., 2017; dos Santos-Fontes et al., 2013; Emmerson et al., 2017; Kimberley et al., 2004; Mortensen et al., 2016; Nijenhuis et al., 2017; Sullivan et al., 2012; Wolf et al., 2015; Zondervan et al., 2016). Unlike the 'no technology' home-based interventions mentioned above, all the interventions (technology-assisted and 'no technology') in these studies were self-

directed or remotely supervised. Only one transcranial direct stimulation study (Mortensen et al., 2016) involved direct supervision by the therapist. Home-based electrical stimulation interventions were more effective than a sham or 'no technology' intervention in improving UL function after treatment and follow-up. This result was consistent with previous reviews (Da-Silva et al., 2018; Yang et al., 2019). Anatomically, the upper limb has high tactile sensitivity, occupying a large area of the somatosensory homunculus (Reed & Ziat, 2018). One proposed explanation for the positive effects of electrical stimulation was that it provides enhanced somatosensory input and increased cognitive sensory attention, which proved to be effective in improving the upper limb's performance in patients with stroke (dos Santos-Fontes et al., 2013; Hara, Ogawa, Tsujiuchi, & Muraoka, 2008). Previous studies highlighted a close relationship between the increased ipsilesional somatosensory cortex (S1) activation and motor improvements induced by training such as CIMT and electrical stimulation (Kimberley et al., 2004; Laible et al., 2012). Most participants in this review were in the chronic stage of stroke (a mean stroke onset time of 23.5 ± 21.2 months). Previous studies (Abdullahi, Truijen, & Saeys, 2020; Laible et al., 2012) had suggested combining electrical stimulation with other interventions such as CIMT in chronic stroke patients would enhance S1 excitability further. Future studies can consider exploring the effectiveness of such a combination conducted in the home to promote cortical reorganization. Another explanation is that the usability of the electrical stimulators used in this review significantly contributes to the positive effects. The electrical stimulators were portable and easy to use. These features allow the participant to manage the devices easily in the home setting with minimal supervision (Hara et al., 2008).

Moreover, the effect of virtual reality was equivalent to "no technology" intervention in improving upper limb function in the home. This observation contradicts recent evidence that favored the effectiveness of virtual reality in improving arm function after stroke (Domínguez-Téllez, Moral-Muñoz, Salazar, Casado-Fernández, & Lucena-Antón, 2020; Laver,

George, Thomas, Deutsch, & Crotty, 2011). Virtual reality (VR) involves the interactive simulation of an environment, scenario, or activity created by a computer, allowing the user to interact through multiple sensory canals (Kwon, Park, Yoon, & Park, 2012; Weiss, Kizony, Feintuch, & Katz, 2006). The Cochrane review (Laver et al., 2011) found that virtual reality was more beneficial when conducted in the first six months and used a minimal training dose of more than 15 hours. One difference was that most of the VR interventions in the Cochrane review (Laver et al., 2011) were conducted in a clinic and under therapists' supervision. Therapists use standardised approaches to guide patients through therapy and motivate them to engage in treatment (Chen et al., 2019). Unlike all the virtual reality interventions in this review, they were mainly self-directed and conducted at home. The lack of a structured session and the absence of therapists might reduce patients' engagement (Chen et al., 2019) and affect the treatment outcome.

The robotic studies showed contrasting outcomes among the other two mentioned interventions. The pooled results favoured traditional home-based exercises without technology in terms of the effect on upper limb function. Consistent with previous studies (Maciejasz et al., 2014; Pollock et al., 2014; Rodgers et al., 2019), robotic-assisted therapy's clinical effect was modest compared to conventional treatment. The robotic-assisted therapy uses power-assisted robotic devices to allow fine-graded upper limb movements and precise measurements (Coscia et al., 2019). One explanation for this unfavourable result was the intensity of the treatment dose. Robotic technology is designed to provide intense, highly repetitive, and task-specific training (Poli, Morone, Rosati, & Masiero, 2013). However, this was not reflected in Nijenhuis's study (Nijenhuis et al., 2017). Nijenhuis et al. (2017) found that their control group had a higher training duration than the robotic group. The marked difference in training duration was attributed to the limited variety of exercises available in the robotic group (i.e. three exercises) versus 34 exercises for the control group (Nijenhuis et al.,

2017). Adherence to training duration is essential, and more attention is needed to motivational strategies when using technology-assisted training (Nijenhuis et al., 2017). A large variety of attractive and functional exercises are crucial to prevent boredom and abandonment and increase adherence (Timmermans, Seelen, Willmann, & Kingma, 2009). Creating various customized exercises while keeping robotic devices affordable can be a potential challenge for robotic therapy. Nevertheless, this observation in the robotic studies necessitates caution in interpretation as there are only two robotic studies available for analysis, limiting the results' generalizability.

2.6 Limitations and Recommendations

Though the studies included in this review demonstrated a low risk of bias in terms of methodological quality, there was substantial heterogeneity between the studies clinically and statistically for one meta-analysis. The included studies varied in the types of interventions used and the time of post-stroke onset among the participants. A range of upper limb outcome measures was used across the studies, making it difficult to compare. This review has included studies from January 2000 to September 2020. Trials before January 2000 and after September 2020 have not been reviewed.

The review's primary outcome focuses on upper limb motor function and use; other domains, such as cost-effectiveness and compliance with interventions, are not evaluated. Further studies are recommended to capture such domains. This review was unable to compare the use of remote-supervised therapy and self-directed therapy due to the limited number of studies using remote supervision (n=4), and they varied in comparison and interventions used.

Use of the affected upper limb in daily activities was self-reported from the Motor Activity Log. Self-report measures are subject to many report biases, such as social desirability

(Adams et al., 2005) and cognitive deficits (i.e., reliance on an individual's recall) (Bradburn, Rips, & Shevell, 1987). Further studies can consider using technology such as an accelerometer to objectively capture arm use in daily activities.

This review demonstrated that home-based UL interventions with direct supervision from the therapist were more effective than in-clinic therapy or technology-assisted interventions delivered under self-directed or remote supervision. Nevertheless, maintaining such a mode of therapy is not sustainable due to the increasing demand for rehabilitation services. Future studies can consider exploring the clinical and cost-effectiveness of a hybrid therapy model in which directly supervised therapy is kept to the minimum and supported with home-based technologies to carry the therapy in a self-directed or remotely supervised manner. Lastly, given the positive effects of home-based electrical stimulation, further studies can consider combining this intervention with home-based CIMT, as proposed by previous studies (Abdullahi et al., 2020; Laible et al., 2012).

2.7 Conclusion

The beneficial effects of home-based upper limb interventions were superior to conventional therapy in improving function and perceived use of the affected upper limb in daily activities. Nevertheless, in an unstructured environment like the home setting, the choice of home-based technology-assisted interventions requires careful consideration of the individual's physical environment, social context, technical proficiency, and motivation (Adie et al., 2017; Chen et al., 2019). Among the home-based interventions, home-based electrical stimulation seemed to provide the most optimal benefits compared to conventional treatment in the home setting.

2.8 Clinical messages

- Home-based upper limb interventions are more effective than conventional therapy in improving the arm function as they provide contextual learning for better translation of skills to the real-life domain.
- When selecting the types of technology-assisted interventions in the home setting, careful considerations of factors such as one's motivation, social context, technical proficiency, physical environment and the therapeutic design and usability of the devices are required.
- The somatosensory input from the electrical stimulation seems to provide the optimal benefits among the home-based upper limb interventions.

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Chapter 3: Application of Home-Based Wearable Technologies in Physical Rehabilitation for Stroke: A Scoping Review

This chapter reviewed the evidence on the application of wearable technologies in home-based stroke rehabilitation. The author of this thesis published this chapter as a scoping review article in IEEE Transactions on Neural System and Rehabilitation Engineering in March 2023. The citation for the scoping review was:

Toh, S. F. M., Fong, K. N. K., Gonzalez, P. C., & Tang, Y. M. (2023). Application of home-based wearable technologies in physical rehabilitation for stroke: A scoping review. *IEEE Transactions on Neural System and Rehabilitation Engineering*, Pp. doi:10.1109/tnsre.2023.3252880

The manuscript, included below, has been formatted according to APA 6th to align with the thesis format. References are provided at the end of the thesis.

3.1 Abstract

Background: Using wearable technologies in the home setting is an emerging option for self-directed rehabilitation. A comprehensive review of its application as a treatment in home-based stroke rehabilitation is lacking. **Objectives:** This review aimed to 1) map the interventions that have used wearable technologies in home-based physical rehabilitation for stroke and 2) provide a synthesis of the effectiveness of wearable technologies as a treatment choice. **Methods:** Electronic databases of the Cochrane Library, MEDLINE, CINAHL, and Web of Science were systematically searched for work published from their inception to February 2022. This scoping review adopted Arksey and O'Malley's framework in the study procedure. Two independent reviewers screened and selected the studies. Twenty-seven were selected in this review. These studies were summarized descriptively, and the level of evidence was assessed. **Results:** Twenty-seven were selected in this review. These studies were summarized descriptively, and the level of evidence was assessed. This review identified that most research focused on improving the hemiparetic upper limb (UL) function and a lack of studies applying wearable technologies in the home-based lower limb (LL) rehabilitation. Virtual reality (VR), stimulation-based training, robotic therapy, and activity trackers are the interventions identified that apply wearable technologies. Among the UL interventions, "strong" evidence was found to support stimulation-based training, "moderate" evidence for activity trackers, "limited" evidence for VR, and "inconsistent evidence" for robotic training. Due to the lack of studies, understanding the effects of LL wearable technologies remains "very limited." **Conclusion:** With newer technologies like soft wearable robotics, research in this area will grow exponentially. Future research can focus on identifying components of LL rehabilitation that can be effectively addressed using wearable technologies.

Index terms- Wearable technology, self-directed rehabilitation, stroke, home-based intervention.

3.2 Introduction

Stroke survivors sustain multiple impairments in physical, cognitive, and sensory functions, significantly impeding their participation in daily activities and impacting their quality of life. For example, 80 percent of stroke survivors face motor impairments affecting one side of their body (Langhorne, Coupar, & Pollock, 2009). Previous research (Hendricks, Van Limbeek, Geurts, & Zwarts, 2002) indicated that only 15 percent of stroke survivors achieve full functional recovery in both limbs. In comparison, 33 to 60 percent have significant residual impairments in their hemiplegic arm at the chronic phase (Kwakkel & Kollen, 2013). Though there have been recent advances in the medical management of stroke, most post-stroke recovery relies heavily on rehabilitation interventions (Langhorne, Sandercock, & Prasad, 2009).

Intensive rehabilitation has been shown to enhance motor recovery after stroke (Kwakkel et al., 2004), and rehabilitation is necessary until maximum recovery is achieved (Intercollegiate Stroke Working Party, 2016). Nevertheless, such extensive training is not sustainable in the long run due to the high cost of post-stroke care, such as rehabilitation services (i.e., therapist salary, rehabilitation site) and hospitalization (Maceira-Elvira, Popa, Schmid, & Hummel, 2019). Therefore, the self-management paradigm has been adopted to facilitate home-based self-directed training to reduce the burden placed on existing healthcare resources (Fryer, Luker, McDonnell, & Hillier, 2016). Self- directed rehabilitation is conducted independently by patients and carers without direct supervision from a healthcare professional. This sort of training at home offers several advantages, such as providing contextual learning in real-life environments that promotes generalization (Trombly & Wu, 1999; von Koch, Wottrich, & Holmqvist, 1998) and reduces the cost of supervised therapy (Saadatnia, Shahnazi, Khorvash, & Esteki-Ghashghaei, 2020).

Wearable technology is a promising option for providing home-based self-directed rehabilitation while keeping costs low (Maceira-Elvira et al., 2019). Using wearable devices offers several advantages over conventional approaches. For example, some devices are portable, low-cost, and flexible (Bonato, 2005; Wang, Markopoulos, Yu, Chen, & Timmermans, 2017). Wearable technologies are electronic hand-free devices worn externally on the body and monitor activities without limiting users' movements (Parker, Powell, & Mawson, 2020; Rodgers, Alon, Pai, & Conroy, 2019). In rehabilitation, wearable technologies are applied to measure body kinematics outside the laboratory and augment posture and motion correction by providing real-time feedback to users (Lee et al., 2021; Wang et al., 2017) or assistance (passive or active assisted) in movements (Marchal-Crespo & Reinkensmeyer, 2009).

Some wearable devices provide real-time augmented feedback by emitting auditory, visual or tactile cues to the user, which is critical for motor relearning (Lee et al., 2021) and sustains motivation during training (Van Vliet & Wulf, 2006). This feedback increases the awareness of correct posture and movement patterns during task execution (Lee et al., 2021; Wang et al., 2017) in stroke individuals whose intrinsic feedback mechanisms (e.g., proprioceptive cues) are weakened or impaired (Van Vliet & Wulf, 2006). Traditionally, the therapist provides extrinsic feedback to facilitate motor relearning in persons with stroke (Wang et al., 2017). However, this training method is very time-consuming and manpower-intensive to carry out at home (Wang et al., 2017). Alternatively, these wearable devices initiate augmented feedback to prompt individuals to perform self-directed training in the home setting. Unlike traditional methods of monitoring therapy adherence, such as using an activity logbook or checklist, the wearable device increases treatment adherence in the home setting by providing objective feedback on the type and amount of upper limb training and triggering sensory reminders to increase the frequency of upper limb practice (Kim, Parnandi, Eva, & Schambra, 2021).

Increasing publication trends on the use of wearable technologies in stroke rehabilitation highlight the growing interest in this area (Kim et al., 2021; Peters et al., 2021). Maceira-Elvira et al. (2019) and Kim et al. (2021) conducted scoping reviews on using UL wearable sensors for assessment and treatment in the stroke population. They found that several studies had focused on hemiparetic UL measurement with sensors, but few focused on treatment approaches, and there is a lack of large-scale studies to prove the clinical efficacy of wearable sensors for home use (Kim et al., 2021). Another study by Peters et al. (2021) focused on reviewing the evidence of wearable sensors for gait assessment and did not look at other types of wearable devices or treatment uses. All these studies (Kim et al., 2021; Maceira-Elvira et al., 2019; Peters et al., 2021) narrowed their scope to wearable sensors; other wearable devices, such as stimulators and robotics, were not explored. Finally, two systematic reviews by Parker et al. (2020) and Powell, Parker, Martyn St-James, and Mawson (2016) investigated the evidence of wearable devices for upper and lower limb rehabilitation, respectively. These reviews included other wearable devices for poststroke rehabilitation, such as electrical stimulation and robotics. Both studies (Parker et al., 2020; Powell et al., 2016) revealed a paucity of high-quality evidence supporting using upper and lower-limb wearable technologies to improve activity and participation. Nevertheless, both narrowed their scope to select randomized controlled studies that used wearable devices to improve activity and participation. Other study designs and outcomes, such as motor impairment and function, were not addressed.

The effects of wearable devices in home-based stroke rehabilitation remained unclear from the analysis of previous reviews (Kim et al., 2021; Parker et al., 2020; Peters et al., 2021; Powell et al., 2016) as most focus on wearable sensors, which are predominantly used for assessment rather than treatment (Kim et al., 2021; Maceira-Elvira et al., 2019; Peters et al., 2021). Augmented feedback from a wearable device may make it an effective tool in motor training for stroke survivors beyond its measurement capabilities. In addition, the current

evidence from previous reviews seems to skew toward using wearable technologies in care institutions or laboratories requiring the supervision of a rehabilitation specialist (Peters et al., 2021; Rodgers et al., 2019), which eliminates stroke survivors' ability to self-direct their training (Peters et al., 2021).

Although earlier studies (Kim et al., 2021; Maceira-Elvira et al., 2019; Parker et al., 2020; Peters et al., 2021; Powell et al., 2016) contributed valuable knowledge to wearable technologies research, a comprehensive review of their application in home-based stroke rehabilitation remains scarce. To the best of our knowledge, no review has investigated the effectiveness of wearable devices as a treatment option in home-based rehabilitation for persons with stroke. A scoping review method is commonly used for new research areas because emerging and diverse evidence clarifies key concepts and characteristics and identifies research gaps (Munn et al., 2018). This scoping review aimed to (1) map interventions that use wearable technologies in home-based physical rehabilitation for stroke and (2) provide a synthesis of their effectiveness as treatment options. The findings of this review shed light on the research gap and aid researchers and clinicians by providing valuable knowledge to translate the use of wearable technologies into clinical practice.

3.3 Method

3.3.1 Design

This scoping review adopted the framework outlined by Arksey and O'Malley (2005), which involves identifying research questions and relevant studies, study selection, charting data, collating, summarizing and reporting results. The Preferred Reporting Items for Systematic Review Extension for Scoping Reviews (PRISMA-ScR) checklist (Tricco et al., 2018) was used to ensure this review's robustness. In addition, the population concept context

(PCC) structure (Peters et al., 2015) was used to identify key elements to conceptualize the scoping review: stroke (Population), wearable technology (Concept), and home (Context).

3.3.2 Search Strategy

A systematic search was conducted on four databases: MEDLINE (via PubMed), CINAHL, Cochrane Library, and Web of Science from inception to February 2022. In addition, the reference lists of eligible studies were hand-searched to identify any potential studies not identified through the database search. The searches were restricted to human studies. Search terms were "wearable," "rehabilitation," and "stroke" and their variations.

3.3.3 Selection Process

The selection process was followed according to the PRISMA guidelines (Moher, Liberati, Tetzlaff, Altman, & Group, 2009). The studies were selected based on the following eligibility criteria: Population: adults (> 18 years old) with stroke; Concept: In this review, wearable devices are defined as electronic "hand-free devices worn externally on the body that are portable (not fixed to a station, i.e., end effector) and can be used independently of a therapist" (Parker et al., 2020; Rodgers et al., 2019) and studies must use wearable devices for treatment purposes; and Context: devices used in the home setting. Duplicates, didactic papers, posters, book chapters, study protocols, conference proceedings, systematic reviews, and meta-analyses were excluded. Studies that did not use stroke subjects and those not published in English were also excluded.

This review recognized that the development of a wearable technology system undergoes different levels of technological "maturity" and adopted the definitions given by

Moral-Munoz, Zhang, Cobo, Herrera-Viedma, and Kaber (2021), see Supplementary information, S2. This review focused on studies that had already piloted a device in the home setting with persons with stroke. Hence, it included studies that coincided with level 5 in technological "maturity".

After completing the database search, duplicates were removed by one reviewer (ST) using Endnote X9 (The Endnote Team., 2013). Two independent reviewers (ST, PC) screened for study eligibility based on titles and abstracts retrieved during the searches using selection criteria. The two reviewers independently reviewed the full text of pre-selected articles and agreed on the final set of included studies. If there was a disagreement regarding the studies to be included, a third reviewer (KNKF) was consulted to achieve consensus.

3.3.4 Data Extraction and Quality Assessment

One reviewer (ST) extracted data from the selected studies using a data charting table, and the second reviewer checked the accuracy (PC). The extracted data included author name, year, study design, sample size, participants, types of interventions, types of feedback, outcome measures, and results. The methodological quality of the selected studies was assessed using the National Institutes of Health (NIH) risk of bias tools for "controlled trial" and "before-after (pre-post studies) studies with no control group" (National Heart Lung and Blood Institute, 2013) by two reviewers (ST and PC). Due to the limited generalizability of the nature of the case study, a case study design is considered a low-quality study in this review. After assessing the methodological quality of the included studies, synthesis was performed to evaluate their evidence level based on a hierarchical criterion, as previously described in other studies (Green & Pizzari, 2017; Lee et al., 2021; Schut et al., 2017; Van Tulder, Furlan, Bombardier, Bouter, & Group, 2003).

3.4 Results

3.4.1 Study selection

The PRISMA diagram (Moher et al., 2009) in Figure 3-1 summarizes the literature search results. The initial search yielded 1,100 articles from the four databases (Cochrane Library n = 1; CINAL n = 49; MEDLINE n = 160; Web of Science n = 883) and hand searching of the reference lists of relevant reviews (n = 7). After removing 113 duplicates, 987 articles were screened. After screening the titles and abstracts, 904 articles were excluded. The full texts of eighty-three articles were obtained for further review. Of these, 27 studies were selected.

3.4.2 Characteristics of selected studies

Table 3-1 provides an overview of 27 chosen studies, which consist of 13 randomized controlled trials (RCTs), 3 non-randomized controlled trials, 9 "before-after" studies, and 2 case studies. Most of the studies (n = 22) (Amirabdollahian et al., 2014; Ballester et al., 2017; Casas et al., 2021; Chae, Kim, Lee, & Park, 2020; Chen, Nichols, Brokaw, & Lum, 2017; Choudhury et al., 2020; Da-Silva et al., 2019; Da-Silva et al., 2018; Dos Santos-Fontes, Ferreiro de Andrade, Sterr, & Conforto, 2013; Durfee, Weinstein, Bhatt, Nagpal, & Carey, 2009; Fang, Mahmoud, Kumar, Gu, & Fu, 2020; Hung et al., 2021; Nijenhuis, Prange-Lasonder, Stienen, Rietman, & Buurke, 2017; Radder et al., 2019; Sanders et al., 2020; Seim, Wolf, & Starner, 2021; Seo et al., 2020; Sullivan, Hurley, & Hedman, 2012; Wei, Fong, Chung, Cheung, & Chow, 2019; Whitford, Schearer, & Rowlett, 2020; Wittmann et al., 2016; Zondervan et al., 2016) applied wearable devices to the UL region, while one (Giansanti, Tiberi, Silvestri, & Maccioni, 2009) focused on the LL region, and three others (Bellomo, 2020; Clarke & Ryan-Bloomer, 2017; Paul et al., 2016) focused on overall physical function. One study (Palmcrantz, Pennati, Bergling, & Borg, 2020) applied wearable devices to upper and lower limb regions.

All the studies selected, except for the case studies, were assessed for their methodological quality. Among the 16 "controlled" studies (Ballester et al., 2017; Chae et al., 2020; Choudhury et al., 2020; Da-Silva et al., 2019; Dos Santos-Fontes et al., 2013; Durfee et al., 2009; Fang et al., 2020; Nijenhuis et al., 2017; Paul et al., 2016; Radder et al., 2019; Sanders et al., 2020; Seim et al., 2021; Seo et al., 2020; Sullivan et al., 2012; Wei et al., 2019; Zondervan et al., 2016), four (Dos Santos-Fontes et al., 2013; Seo et al., 2020; Sullivan et al., 2012; Wei et al., 2019) were categorized as of "high" methodological quality, seven (Ballester et al., 2017; Choudhury et al., 2020; Da-Silva et al., 2019; Nijenhuis et al., 2017; Radder et al., 2019; Seim et al., 2021; Zondervan et al., 2016) as "fair," and the remaining five (Chae et al., 2020; Durfee et al., 2009; Fang et al., 2020; Paul et al., 2016; Sanders et al., 2020) as "low." Table 3-2 details the methodological quality assessment for the "controlled" studies. Of the "before-after" studies (n = 9) (Amirabdollahian et al., 2014; Bellomo, 2020; Casas et al., 2021; Chen et al., 2017; Da-Silva et al., 2018; Hung et al., 2021; Palmcrantz et al., 2020; Whitford et al., 2020; Wittmann et al., 2016), two (Bellomo, 2020; Palmcrantz et al., 2020) were categorized as "fair," and seven (Amirabdollahian et al., 2014; Casas et al., 2021; Chen et al., 2017; Da-Silva et al., 2018; Hung et al., 2021; Whitford et al., 2020; Wittmann et al., 2016) were considered "low" quality. See Table 3-3.

Figure 3-1: Prisma diagram on search results

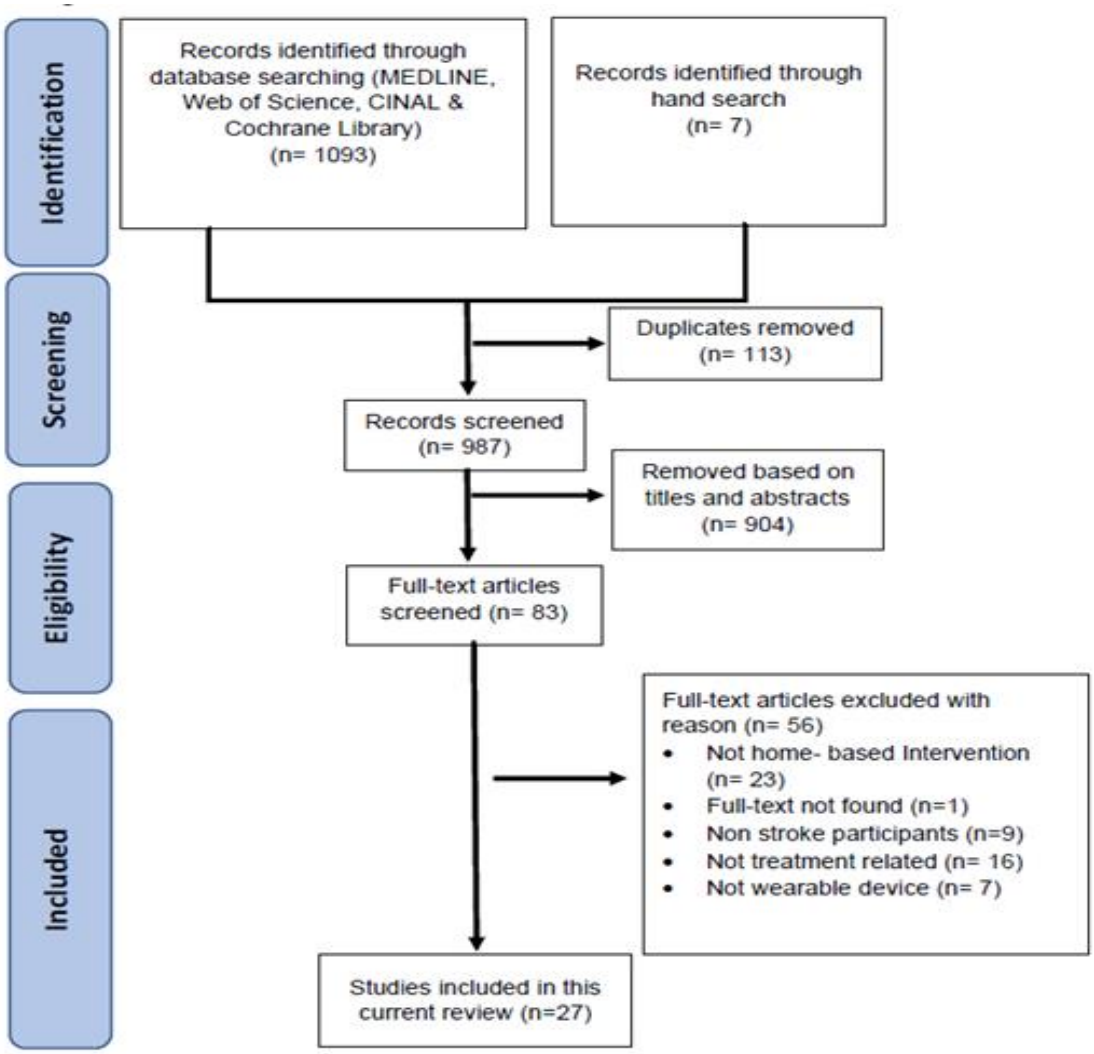


Table 3-1: Characteristics of selected studies

Category	Study	Study Design	Sample size (n)	Quality rating	Outcome	Level of evidence
Upper limb						
Sensorimotor stimulation	Choudhury et al. [38]	RCT	E1: 32 E2: 32 C: 31	Fair	+ effect on UL function	Strong evidence
	dos Santos-Fontes et al. [41]	RCT	E: 10 C: 10	Good		
	Seim et al. [48]	RCT	E: 8 C:8	Fair		
	Sullivan et al. [50]	RCT	E: 20 C:18	Good		
	Seo et al. [49]	RCT	E: 13 C:13	Good	√ feasible to use	
Activity trackers	Chae et al. [36]	Non-RCT	E: 26 C:12	Poor	+ effect on UL function	Moderate evidence
	Da-Silva et al. [40]	'Before-after'	E:7	Poor		
	Da-Silva et al. [39]	RCT	E: 14 C:19	Fair		
	Wei et al. [51]	RCT	E1: 32 E2: 25 C: 27	Good		
	Whitford et al. [52]	'Before-after'	E: 8	Poor		
Virtual reality	Ballester et al. [34]	RCT	E: 17 C:18	Fair	+ effect on UL function	Limited evidence
	Durfee et al. [42]	Non-RCT	E: 10 C:10	Poor		
	Fang et al. [43]	RCT	E: 20 C:6	Poor		
	Hung et al. [44]	'Before-after'	E: 23	Poor		
	Wittman et al. [53]	'Before-after'	E: 11	Poor		
	Zondervan et al. [54]	RCT	E: 9 C:8	Fair		
	Sanders et al. [47]	RCT	E: 6 C:5	Poor	√ feasible to use	
Robotics	Amirabdollahian et al. [33]	'Before-after'	E: 12	Poor	+ effect on UL function	Inconsistent evidence
	Casa et al. [35]	'Before-after'	E: 10	Poor		
	Chen et al. [37]	'Before-after'	E: 10	Poor		
	Radder et al. [46]	RCT	E1: 30 E2: 28 C: 33	Fair		
	Nijenhuis et al. [45]	RCT	E: 9 C:10	Fair	- effect on UL function	
Lower limb						
Virtual reality	Giansanti et al. [55]	Case study	E:1	Poor	+ effect on LL function	Very limited evidence
Both limbs						
Sensorimotor stimulation	Palmcrantz et al. [59]	'Before-after' study	E: 20	Fair	+ effect on UL & LL function	Very limited evidence
Physical function						
Activity trackers	Clarke & Bloomer [58]	Case study	E:1	Poor	+ effect on physical function	Very limited evidence
	Paul et al. [57]	Non RCT	E: 15 C:8	Poor		
Virtual reality	Bellomo et al. [56]	'Before-after'	E: 22	Fair	+ effect on physical function	

Legend: +: positive; - no superior ; √ supported, E: experiment; C: control; LL: lower limb; n: number; RCT: randomized controlled trial; UL: upper limb (for detail of the studies, refer to supplementary information, S4)

Table 3-2: Risk-of-bias evaluation for randomized controlled trials (n=16) using the National Health Institutes of Health risk-bias tool for controlled trials

Study	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Quality rating
Ballester et al. [34]	√	√	NR	-	-	√	√	√	NR	NR	√	-	NR	-	Fair
Chae et al. [36]	-	-	-	-	-	√	-	-	NR	√	√	√	√	-	Poor
Choudhury et al. [38]	√	√	-	-	√	√	-	-	-	-	√	NR	√	√	Fair
Da-Silva et al. [39]	√	√	NR	-	√	-	-	-	-	NR	√	-	√	-	Fair
dos Santos-Fontes et al. [41]	√	√	√	-	√	√	√	√	-	NR	√	-	NR	√	Good
Durfee et al. [42]	-	-	-	-	-	-	√	√	√	NR	√	-	-	-	Poor
Fang et al. [43]	√	√	NR	-	-	NR	-	-	-	√	√	-	-	-	Poor
Nijenhuis et al. [45]	√	√	√	-	-	√	√	√	-	NR	√	-	NR	-	Fair
Paul et al. [57]	-	-	-	-	-	√	√	√	NR	NR	√	-	-	-	Poor
Radder et al. [46]	√	√	-	-	-	NR	√	-	-	NR	√	-	-	NR	Fair
Sanders et al. [47]	√	-	-	-	√	-	-	-	-	√	√	-	√	-	Poor
Seim et al. [48]	√	-	-	√	√	NR	√	-	NR	√	√	-	NR	√	Fair
Seo et al. [49]	√	√	√	√	√	√	√	√	√	√	√	√	√	√	Good
Sullivan et al. [50]	√	√	NR	-	√	√	√	√	√	NR	√	√	√	-	Good
Wei et al. [51]	√	√	-	-	√	√	√	-	-	+	√	√	√	√	Good
Zondervan et al. [54]	√	√	-	-	√	-	√	√	-	NR	√	√	√	-	Fair

Legend: √ met criteria; - did not meet criteria; CD: cannot be determined; NR: not reported

NIH controlled trial criteria: (1) Study description, RCT, (2) Adequate method of randomization, (3) Concealment of treatment allocation, (4) Blinding of participants and providers, (5) Blinding of assessor, (6) similar baseline characteristics, (7) Dropout rate 20% or less, (8) Differential dropout rate 15% or lower, (9) High treatment adherence, (10) Other interventions avoided or similar among groups, (11) Reliable and valid outcome measures, (12) Adequate sample size, (13) Outcomes reported, subgroup analysed prespecified, (14)Participants analysed in the group to which they were originally assigned (i.e. intention to treat)

Table 3 -3: Risk-of-bias evaluation for 'before-after' design (n=9) using the National Health Institutes of Health risk-bias tool for 'before-after' studies (without control group)

Study	1	2	3	4	5	6	7	8	9	10	11	12	Quality rating
Amirabdollahian et al. [33]	√	-	NR	-	-	NR	-	-	NR	-	-	NA	Poor
Bellomo et al. [56]	√	√	√	√	√	√	√	-	√	√	-	NA	Fair
Casas et al. [35]	√	√	√	√	-	-	√	-	-	√	-	NA	Poor
Chen et al. [37]	√	√	√	√	-	√	√	-	-	√	-	NA	Poor
Da-Silva et al. [40]	√	NR	√	√	-	√	√	-	-	√	-	NA	Poor
Hung et al. [44]	√	√	√	√	-	√	NR	√	-	NR	√	NA	Poor
Palmcrantz et al. [59]	√	√	√	√	-	√	√	-	√	√	-	NA	Fair
Whitford et al. [52]	√	√	√	√	-	√	√	-	√	√	-	NA	Poor
Wittmann et al. [53]	√	√	√	√	-	-	√	-	-	√	-	NA	Poor

Legend: + met criteria; - did not meet criteria; CD: cannot be determined; NR: not reported; NA: not applicable

NIH criteria for 'before-after' studies: (1) Study question or objective clearly stated, (2) Eligibility criteria stated, (3) Participants representative of the general population, (4) All eligible participants enrolled, (5) Adequate sample size, (6) Intervention/test clearly described, (7) Valid and reliable outcome measures used, (8) Blinding of assessors, (9) Loss to follow <20%, (10) Statistical test of outcome measures measured, (11) Outcome measures conducted at multiple times before and after test, (12) Intervention conducted at group level, use individual data at group.

The total number of participants in the included studies was 717, with sample sizes ranging from 1 to 95. The mean age of the participants was 60.4 (5.3) years. Two studies (Giansanti et al., 2009; Sanders et al., 2020) did not report the age of their participants. The mean stroke onset of the participants was 34.8 (22.6) months. Seven studies (Chae et al., 2020; Clarke & Ryan-Bloomer, 2017; Fang et al., 2020; Giansanti et al., 2009; Hung et al., 2021; Radder et al., 2019; Sanders et al., 2020) did not indicate the time of their participants' stroke onset.

3.4.3 Types of Wearable Technologies Applied to Stroke Rehabilitation

This review identified four types of interventions applying wearable technologies to home-based stroke rehabilitation -virtual reality (VR), robotics, sensorimotor stimulation, and activity trackers. Most studies applied wearable technologies in VR training (n = 9) (Ballester et al., 2017; Bellomo, 2020; Durfee et al., 2009; Fang et al., 2020; Giansanti et al., 2009; Hung et al., 2021; Sanders et al., 2020; Wittmann et al., 2016; Zondervan et al., 2016), followed by activity trackers (n=7) (Chae et al., 2020; Clarke & Ryan-Bloomer, 2017; Da-Silva et al., 2019; Da-Silva et al., 2018; Paul et al., 2016; Wei et al., 2019; Whitford et al., 2020) and sensorimotor stimulation (n =6) (Choudhury et al., 2020; Dos Santos-Fontes et al., 2013; Palmcrantz et al., 2020; Seim et al., 2021; Seo et al., 2020; Sullivan et al., 2012). Five studies (Amirabdollahian et al., 2014; Casas et al., 2021; Chen et al., 2017; Nijenhuis et al., 2017; Radder et al., 2019) applied wearable technologies in robotic training.

With recent technological advancements, the use of wearable sensors has grown exponentially (Keogh, Taraldsen, Caulfield, & Vereijken, 2021). 81 percent of the studies (n=22) (Amirabdollahian et al., 2014; Ballester et al., 2017; Bellomo, 2020; Casas et al., 2021; Chae et al., 2020; Chen et al., 2017; Clarke & Ryan-Bloomer, 2017; Da-Silva et al., 2019; Da-Silva et al., 2018; Durfee et al., 2009; Fang et al., 2020; Giansanti et al., 2009; Hung et al., 2021; Nijenhuis et al., 2017; Paul et al., 2016; Radder et al., 2019; Seim et al., 2021; Wei et al., 2019; Whitford et al., 2020; Wittmann et al., 2016; Zondervan et al., 2016) used pressure sensors, inertial measurement units, and electromyography sensors to collect kinematic and muscle activity data. Only five sensorimotor stimulation studies (Choudhury et al., 2020; Dos Santos-Fontes et al., 2013; Palmcrantz et al., 2020; Seo et al., 2020; Sullivan et al., 2012) did not use sensors.

1) Virtual reality: VR is a form of training where patients interact with a virtual or augmented environment created with the aid of technology (Weiss et al., 2006). There are two

types of VR: immersive and non-immersive. Immersive VR rehabilitation provides a training environment that refocuses users' sensations from the real to the virtual world (Slater, 2003). This type of training usually includes using a head-mounted display or goggles, which can screen out other stimulation from the virtual environment (Cho & Lee, 2019). Unlike immersive VR, non-immersive VR allows users to see the screen environment (Cho & Lee, 2019) and interact with the VR task on-screen (Weiss, Rand, Katz, & Kizony, 2004). Examples of non-immersive VR rehabilitation are offered by Kinect, Nintendo Wii, and IREX. Only studies that used wearable devices in VR training were included in this review. Studies that used video-captured VR (i.e., Kinect, Nintendo Wii) without any wearable interface were excluded.

Nine of the included studies (Ballester et al., 2017; Bellomo, 2020; Durfee et al., 2009; Fang et al., 2020; Giansanti et al., 2009; Hung et al., 2021; Sanders et al., 2020; Wittmann et al., 2016; Zondervan et al., 2016) used wearable sensors in VR training, all non-immersive. Nearly half of these studies (Bellomo, 2020; Durfee et al., 2009; Fang et al., 2020; Giansanti et al., 2009) used information communication technology to monitor participants' progress remotely. The wearable sensors in the VR systems upload data to an encrypted cloud server, allowing the therapist to monitor the participant's progress and provide timely feedback remotely. Interactive therapy (i.e., VR) and remote monitoring promote engagement and sustain users' motivation, which is essential for unsupervised therapy at home. Cramer et al. (2019) stressed that sustaining the participant's motivation in unsupervised home-based therapies is challenging, and previous studies have reported high nonadherence levels of up to 70 percent (McLean, Burton, Bradley, & Littlewood, 2010). Remote monitoring from the therapist mitigates this risk of non-adherence by promoting therapist-client interaction and offering timely feedback (Evangelista et al., 2015). Finally, all the VR studies used a monitor

(computer screen or television) or tablet as their visual display. The use of more portable devices, such as smartphones, has yet to be explored.

2) Activity trackers: Seven studies (Chae et al., 2020; Clarke & Ryan-Bloomer, 2017; Da-Silva et al., 2019; Da-Silva et al., 2018; Paul et al., 2016; Wei et al., 2019; Whitford et al., 2020) used wearable devices as activity trackers. Five (Chae et al., 2020; Da-Silva et al., 2019; Da-Silva et al., 2018; Wei et al., 2019; Whitford et al., 2020) used these devices to track the use of impaired arms, while two (Clarke & Ryan-Bloomer, 2017; Paul et al., 2016) used them to track participants' physical activity. All the wearable devices used in these studies, except for one (Paul et al., 2016), resembled a wristwatch, and participants were instructed to wear it for a predetermined period. The study by Paul et al. (2016) used a smartphone as a wearable device and instructed participants to use a pouch to carry with it. All the studies used the tracked activity data to promote participants' awareness of their activity level. The activity trackers in more than two-thirds of these studies (Clarke & Ryan-Bloomer, 2017; Da-Silva et al., 2019; Da-Silva et al., 2018; Paul et al., 2016; Wei et al., 2019) emitted visual and/or vibration signals to prompt participants to move their impaired arms or increase their physical activity level. Two studies (Chae et al., 2020; Whitford et al., 2020) used the tracked activity data to provide summary feedback to participants on their performance during the therapy visit.

3) Sensorimotor stimulation: Five studies (Choudhury et al., 2020; Dos Santos-Fontes et al., 2013; Seim et al., 2021; Seo et al., 2020; Sullivan et al., 2012) used wearable devices to provide sensorimotor stimulation to treat the hemiparetic arm. One study (Palmcrantz et al., 2020) used a full-body wearable suit to stimulate the upper and lower limbs. These studies used two types of stimulation: electrical and vibratory. Two-thirds of the studies (n = 4) (Choudhury et al., 2020; Dos Santos-Fontes et al., 2013; Palmcrantz et al., 2020; Sullivan et al., 2012) used electrical stimulation on muscles or nerves, while the remaining two (Seim et al., 2021; Seo et al., 2020) used vibration to stimulate the skin underneath the device (i.e., the dorsum of the

wrist or hand). Unlike electrical stimulation, vibratory stimulation can be applied mechanically with or without the placement of an electrode. The two types of stimulation also differ in mechanism: electrical stimulation targets the tissue responses from the nerves or muscles (Knight & Draper, 2013), while vibratory stimulation targets the cutaneous mechanoreceptors underneath the skin and afferents (Vallbo, 2018; Vallbo & Johansson, 1984).

4) Robotics: Five studies (Amirabdollahian et al., 2014; Casas et al., 2021; Chen et al., 2017; Nijenhuis et al., 2017; Radder et al., 2019) hemiparetic UL function. Robotic devices are wearable interactive motorized devices that allow fine-graded limb movements (Coscia et al., 2019) and provide passive, active assisted, or resistive training (Marchal-Crespo & Reinkensmeyer, 2009). These wearable robotic devices enable repetitive, intensive, and task-specific training to promote motor learning (Fasoli, 2016). Wearable soft robotics (WSR) is increasingly attracting researchers' interest in wearable technologies research (Thalman & Artemiadis, 2020). WSR devices use soft and flexible garment-like materials, making them more lightweight (Radder et al., 2019) and offering more flexibility and versatility for the user's comfort and ease of use (Thalman & Artemiadis, 2020).

Nevertheless, this review found that the clinical application of WSR in home-based stroke rehabilitation remains limited. Due to its novelty, only one study (Radder et al., 2019) identified in this review used a wearable soft robotic glove to provide UL training for persons with hand limitations. Four other robotics studies (Amirabdollahian et al., 2014; Casas et al., 2021; Chen et al., 2017; Nijenhuis et al., 2017) used a rigid wearable hand exoskeleton called a handspring-operated movement enhancer (HANDSOME) or a mechatronic device called SCRIPT Prototype 1. This type of wearable exoskeleton resembles a wrist, hand, and finger orthosis with a passive actuation mechanism to aid users in grasping and releasing objects. In addition, three robotic studies (Amirabdollahian et al., 2014; Nijenhuis et al., 2017; Radder et

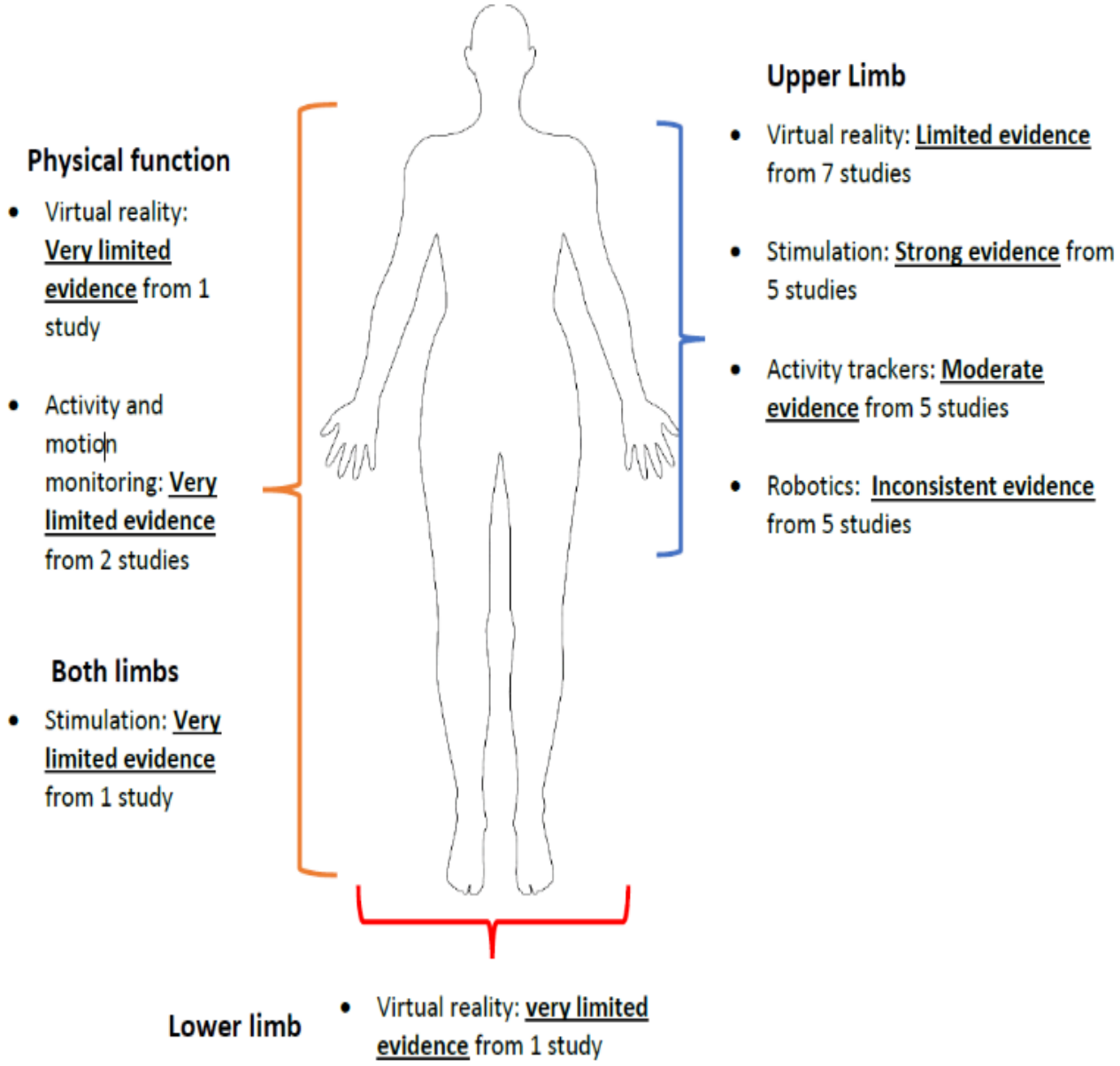
al., 2019) integrated their robotic devices into a VR system to increase the engagement of their participants.

3.4.4 Effects of interventions using Wearable Technologies

This review analyzed the quality of evidence on the effect of the four modalities mentioned above. The synthesis of the quality of evidence (Figure 3-2 & Table 2-1) identified a wide variation in the level of evidence concerning their effect in the different targeted regions, such as the hemiparetic UL, LL, and physical function.

1) Intervention effect on hemiparetic UL: Twenty-two studies (Amirabdollahian et al., 2014; Ballester et al., 2017; Casas et al., 2021; Chae et al., 2020; Chen et al., 2017; Choudhury et al., 2020; Da-Silva et al., 2019; Da-Silva et al., 2018; Dos Santos-Fontes et al., 2013; Durfee et al., 2009; Fang et al., 2020; Hung et al., 2021; Nijenhuis et al., 2017; Radder et al., 2019; Sanders et al., 2020; Seim et al., 2021; Seo et al., 2020; Sullivan et al., 2012; Wei et al., 2019; Whitford et al., 2020; Wittmann et al., 2016; Zondervan et al., 2016) in this review evaluated the effect of interventions using wearable technologies on the hemiparetic UL. These studies used VR, robotics, activity trackers, and sensorimotor stimulation interventions. Concerning the effectiveness of the interventions in improving hemiparetic UL outcomes, this review found a “strong” level of evidence supporting the use of sensorimotor stimulation, a “moderate” level of evidence supporting the use of activity trackers, a “limited” level of evidence supporting VR training, and “inconsistent” evidence for the use of wearable robots.

Figure 3 -2: Level of evidence in applying wearable technologies to different regions



Five RCT studies (Choudhury et al., 2020; Dos Santos-Fontes et al., 2013; Seim et al., 2021; Seo et al., 2020; Sullivan et al., 2012) contributed to the "strong" evidence of the effectiveness of sensorimotor stimulation in improving hemiparetic UL function. Among these studies, three (Dos Santos-Fontes et al., 2013; Seo et al., 2020; Sullivan et al., 2012) were rated as being of "high" quality, and two (Choudhury et al., 2020; Seim et al., 2021) were of "fair" quality for their methodology. All the studies but one (Seo et al., 2020) reported improvements in the motor performance of the hemiparetic UL in their participants after stimulation. Seo et al. (2020) did not assess their participants' arm performance. Instead, the authors (Seo et al., 2020) evaluated the safety aspect of applying a wearable vibrator at home, demonstrating the safe application of the device for long-term daily use at home. "Moderate" evidence was found in five studies (Chae et al., 2020; Da-Silva et al., 2019; Da-Silva et al., 2018; Wei et al., 2019; Whitford et al., 2020) that used wearable technologies as activity trackers. Though all the studies supported the effectiveness of the activity trackers in improving impaired arm function, they varied in their study quality and design. There was one "high"-quality RCT (Wei et al., 2019), one "fair"-quality RCT (Da-Silva et al., 2019), one "low"-quality non-RCT (Chae et al., 2020) and two "low"-quality "before-after" studies (Da-Silva et al., 2018; Whitford et al., 2020).

As for the VR interventions, "limited evidence" from seven studies (Ballester et al., 2017; Durfee et al., 2009; Fang et al., 2020; Hung et al., 2021; Sanders et al., 2020; Wittmann et al., 2016; Zondervan et al., 2016) supported its effectiveness. Three (Fang et al., 2020; Hung et al., 2021; Wittmann et al., 2016) targeted gross motor arm movement, while four focused on distal hand function (Ballester et al., 2017; Durfee et al., 2009; Sanders et al., 2020; Zondervan et al., 2016). Sanders et al. (2020) demonstrated the feasibility of using their VR system as a home-based UL intervention. Although the remaining six studies (Ballester et al., 2017; Durfee et al., 2009; Fang et al., 2020; Hung et al., 2021; Wittmann et al., 2016; Zondervan et al., 2016)

supported the use of VR training to improve the perceived and actual performance of the hemiparetic arm, the quality of their evidence is limited by the study design and method used. No high-quality VR study was found. The seven studies consisted of two "fair"-quality RCTs (Ballester et al., 2017; Zondervan et al., 2016), two "low"-quality RCTs (Fang et al., 2020; Sanders et al., 2020) and three "low"-quality studies (Durfee et al., 2009; Hung et al., 2021; Wittmann et al., 2016) that used either non-randomized controlled or a "before-after" study design. Lastly, there was an "inconsistent" level of evidence concerning the effectiveness of robotic training in five studies (Amirabdollahian et al., 2014; Casas et al., 2021; Chen et al., 2017; Nijenhuis et al., 2017; Radder et al., 2019). These studies focused on improving the distal hand function of the hemiparetic arm. Three "low"-quality "before-after" studies (Amirabdollahian et al., 2014; Casas et al., 2021; Chen et al., 2017) and one "fair"-quality RCT (Radder et al., 2019) reported a beneficial effect of robotic interventions over conventional therapy. One "fair"- quality RCT (Nijenhuis et al., 2017) did not find a similar beneficial effect.

2) Intervention effect on hemiparetic LL and physical function: This review revealed a paucity of studies that applied wearable technologies in home-based LL rehabilitation for persons with stroke. Only one case study (Giansanti et al., 2009) was found that applied a home-based telerehabilitation system supported by wearable insole sensors to improve the gait of a single subject. Though this study reported favorable outcomes, its level of evidence was regarded as "low." Therefore, the overall evidence in this area was considered "very limited". Similarly, "very limited" evidence from three studies (Bellomo, 2020; Clarke & Ryan-Bloomer, 2017; Paul et al., 2016) was available to support the effectiveness of wearable technology interventions in improving the physical function of stroke participants. Two studies (Clarke & Ryan-Bloomer, 2017; Paul et al., 2016), a case study and a non-randomized controlled trial, used activity trackers to improve participants' physical function. Another "before-after" study (Bellomo, 2020) used VR training instead. Although all these studies (Bellomo, 2020; Clarke

& Ryan-Bloomer, 2017; Paul et al., 2016) reported favorable outcomes for the participants' physical function, the overall evidence was considered "low"-quality due to the high risk of bias linked to the methods used.

3.5 Discussion

This scoping review mapped the current home-based stroke rehabilitation interventions that use wearable technologies and provided a synthesis of evidence concerning the effectiveness of these interventions. Four types of interventions that applied wearable technologies in home-based stroke rehabilitation were identified - VR, stimulation-based training, robotic therapy, and activity trackers. This review uncovered varying evidence concerning the effectiveness of these interventions in the different targeted regions, such as the hemiparetic upper limb, lower limb, and overall physical function. Most studies on wearable technology research in the home focused on improving the hemiparetic UL, while few concentrated on the lower limb region and overall physical function. In the following section, we discussed the effects of wearable technology interventions and future research directions.

3.5.1 Effects of Wearable Technology Interventions

Overall, most of the reported outcomes of interventions that used wearable technologies in stroke rehabilitation were positive, such as improved paretic UL function and increased walking and physical activity. Nevertheless, a synthesis of the evidence on the intervention effect on the hemiparetic arm highlights two key findings. This review found "strong" evidence supporting the effectiveness of stimulation-based interventions and an "inconsistent" level concerning wearable robotic training.

Somatosensory input provided by wearable stimulation devices appeared to be effective in improving hemiparetic arm outcomes. The effectiveness of somatosensory stimulation in improving arm motor function has been debated in previous systematic reviews that reported varying success (Grant, Gibson, & Shields, 2018; Yang et al., 2019). A meta-analysis (Yang et al., 2019) demonstrated that electrical stimulation effectively improved the hemiplegic arm function of persons with stroke. This study included the results of 48 RCTs and found that the electrical stimulation group showed more significant improvement in the affected arm than the control group. In contrast, another systematic review (Grant et al., 2018) reported low to moderate–quality evidence from 15 studies suggesting that somatosensory stimulation did not improve hemiparetic arm function. Nonetheless, it is notable that the review included studies that used thermal and compression therapy that shared different mechanisms from the electrical or vibratory stimulation used in the studies selected here. In this review (Grant et al., 2018), the selected sensorimotor stimulation studies used a high treatment dose (i.e., average total treatment dose: 102.5 hours). High doses provide enhanced somatosensory stimulation, which is believed to have a priming effect inducing changes in motor cortical excitability (Golaszewski et al., 2012; Grant et al., 2018). Previous studies supported that enhanced somatosensory input from electrical stimulation improves the hemiplegic UL function in persons with stroke (Dos Santos-Fontes et al., 2013; Hara, Ogawa, Tsujiuchi, & Muraoka, 2008). Another recent RCT also found that vibration stimulation enhanced neural communication in the cortical sensorimotor network in their participants (Schranz, Vatinno, Ramakrishnan, & Seo, 2022).

Another explanation is that sensorimotor stimulation, such as electrical stimulation, has been used as rehabilitation technology with hemiplegic patients for more than 30 years (Coscia et al., 2019). This technology is considered relatively mature and has been proved to be effective in stroke rehabilitation, where its clinical validity and safety are established. With a

high level of technology maturity, more large-scale and well-designed studies are conducted, contributing to the high-quality evidence found in this review.

Another key finding is the "inconsistent" evidence concerning the effectiveness of wearable robotic training in home-based UL rehabilitation. This finding is consistent with previous reviews (Maciejasz, Eschweiler, Gerlach-Hahn, Jansen-Troy, & Leonhardt, 2014; Pollock et al., 2014) that showed the benefits of the effectiveness of robotic training over conventional therapy was debatable. The Cochrane review by Pollock et al. (2014) and the review by Maciejasz et al. (2014) found insufficient evidence supporting the effectiveness of robotic training over conventional therapy to improve the hemiplegic UL function.

Furthermore, applying robotic therapy in the home poses additional challenges to developers and researchers. Traditionally, robotic training has been used in the laboratory or hospital due to the cost and size of the equipment and the need for a skilled operator (Kutlu, Freeman, & Spraggs, 2017; Manjunatha et al., 2021). One also needs to consider the variety of exercises that robotic therapy can offer to sustain participants' engagement. For instance, one RCT (Nijenhuis et al., 2017), the main contributor to the "inconsistent" evidence in robotic therapy, found a significantly lower adherence in the robotic group due to the limited variety of exercises offered by the robotic system. It has also been observed that fewer than half of the wearable robotics studies (Nijenhuis et al., 2017; Radder et al., 2019) used an RCT design. This observation implies the existence of challenges in designing and developing a robotic system suitable for home use. Home-based robotic technology is still maturing, and further fine-tuning is needed.

This review revealed a paucity of research on wearable technologies in home-based LL rehabilitation. The literature search found that studies (Choi, Choi, Gang, Jung, & Kim, 2021; Ma, Zheng, & Lee, 2018; Schifino et al., 2021) that applied wearable technologies in LL stroke

rehabilitation had predominantly carried out interventions in the laboratory or hospital setting. In addition, all these studies (Choi et al., 2021; Ma et al., 2018; Schifino et al., 2021) were at the "proof of concept" stage with small-scale study designs such as case studies or single groups. The application of wearable technologies to improve LL outcomes seems to be at an early stage, such as level 2 of technology "maturity" described by Moral-Munoz et al. (2021).

One intention of home-based technology-assisted interventions such as wearable technology is to offer a platform for unsupervised or under-supervised therapy, reducing the need for the physical presence of a therapist. This approach may not be suitable for certain types of LL rehabilitation, such as balance training. A previous systematic review (Appleby et al., 2019) highlighted that remote supervision delivered through telerehabilitation was ineffective compared to usual care for balance training. Patients require adequate safeguards and physical assistance during balance training, so in-person rehabilitation may be more appropriate than remote mode (Appleby et al., 2019). Further studies can consider identifying the components of LL rehabilitation that can be effectively addressed by wearable technologies and those that require supervised therapy.

3.5.2 Future research directions

Smartphones' popularity and high ownership rate globally (Moral-Munoz et al., 2021) offer new opportunities for VR rehabilitation. Smartphones are portable and offer more flexibility for users to conduct training in their preferred location. All the VR training in the selected studies used a monitor or tablet as the visual display, which requires some setup and takes up physical space in the home. Future studies can explore using smartphones as the visual display for VR training.

Stroke survivors learn to compensate for their motor impairment by not involving or using their hemiparetic UL in daily activities (Jaafar, Che Daud, Ahmad Roslan, & Mansor, 2021); this is commonly known as a learned non-use phenomenon. The consequence is that therapeutic gains from the prescribed intervention deteriorate rapidly over time (Jaafar et al., 2021; Michielsen et al., 2011). One valuable feature of wearable sensors is that they can track activity and prompt individuals to use the impaired arm in their daily routine outside the "prescribed therapy" time. Furthermore, a similar type of sensor is used in VR training. Future development can consider harnessing the full potential of wearable sensors to develop a device that can support "prescribed" therapy in real environments and be used as an activity tracker to prompt users to use their impaired limbs outside therapy time. In this way, it addresses the need for intensive practice of the impaired limbs in daily routine to sustain therapeutic gains.

3.5.3 Limitations

This review was limited to the studies that used wearable technologies to provide stroke rehabilitation in the home. Furthermore, it focused on studies that conducted clinical trials on the target population (i.e., persons with stroke) with technological "maturity" of level 5. Other studies that have applied wearable technologies of a lower technology "maturity" level in the clinical or laboratory setting exist, but they were not within the scope of this review.

3.6 Conclusion

Wearable technologies have the potential to provide intensive home-based therapy in a self-directed manner for persons with stroke. With newer technologies such as soft wearable robotics and telerehabilitation emerging, research in wearable technologies for home use will grow exponentially. This review identified that most current research focuses on the UL, and there is a paucity of studies concerning LL rehabilitation. Future studies can consider identifying components of LL rehabilitation that can be effectively addressed by wearable technologies and those that require supervised therapy.

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Chapter 4: Usability of a wearable device for home-based upper limb telerehabilitation in persons with stroke: A mixed-methods study

This chapter explored the usability of a novel wearable device, 'Smart Reminder' for home-based telerehabilitation for persons with stroke. This chapter was published by the author of this thesis as a mixed method study in Digital Health in January 2023. The citation for this study was:

Toh, S. F. M., Gonzalez, P. C., & Fong, K. N. K. (2023). Usability of a wearable device for home-based upper limb telerehabilitation in persons with stroke: A mixed-methods study. *Digital health*, 9, 20552076231153737-20552076231153737. doi:10.1177/20552076231153737

The manuscript, included below, has been formatted according to APA 6th to align with the thesis format. References are provided at the end of the thesis.

4.1 Abstract

Background: The use of wearable technology offers a promising home-based self-directed option for upper limb training. Although product usability is a crucial aspect of users' acceptance of a wearable device, usability studies in wearable devices are rare, with most studies focusing primarily on clinical validity. **Objectives:** This study aimed to explore the usability of a wristwatch device called "Smart reminder" for home-based upper limb telerehabilitation for persons with stroke. **Methods:** Eleven stroke participants used the proposed wristwatch for at least two weeks and underwent a home-based telerehabilitation program. A mixed-methods design was used to explore the usability of the wristwatch. Quantitative data were collected through the System Usability Scale (SUS) questionnaire, and the participants' rate of therapy compliance (gathered from the device) was reported descriptively. In addition, qualitative data were collected through semi-structured interviews with the participants and were analyzed using thematic analysis. **Results:** The results demonstrated that the usability of the proposed wristwatch and telerehabilitation system was rated highly by the participants, with a high SUS mean score of 84.3 (12.3) and a high therapy compliance rate (mean=91%). Qualitatively, all participants reported positive experiences with the wristwatch and indicated keenness to use it again. Participants reported physical improvements and felt motivated to exercise after using the wristwatch. They found the device easy and convenient and appreciated the remote monitoring function. Meanwhile, they highlighted critical considerations for the design of the device and program, including technical support, a wearable design of the device, graded exercise content according to ability, and flexibility in exercise schedules. Finally, they suggested that an interim review with the therapist on their progress might help them continue using the wristwatch. **Conclusion:** This study's results supported the proposed wearable device's usability and showed strong acceptance by the participants for using it as a home-based upper limb telerehabilitation intervention.

Keywords- Home-based interventions, wearable technology, telerehabilitation, stroke, usability

4.2 Introduction

Upper limb disability in stroke survivors poses a significant challenge to rehabilitation practitioners (Brauer, Hayward, Carson, Cresswell, & Barker, 2013), and further research on rehabilitation to improve the performance of paretic upper limbs is recognized as a top priority of stroke survivors, carers, and healthcare practitioners (Pollock, St George, Fenton, & Firkins, 2012). Intensive and frequent task-specific practice is known to improve upper limb recovery after stroke (Pollock et al., 2014; Timmermans et al., 2009; Van Peppen et al., 2004), but it can be resource-demanding when carried out in person. Therefore, there is an increasing emphasis on self-directed upper limb training through empowering patients and caregivers in the home (Da-Silva et al., 2018; Harris, Eng, Miller, & Dawson, 2009). Home-based training provides context-dependent learning and uses objects of daily relevance to the patients (Cunningham, Turton, Van Wijck, & Van Vliet, 2016; Trombly & Wu, 1999). The use of wearable technology offers a promising option as a form of home-based self-directed upper limb training while keeping costs low (Maceira-Elvira, Popa, Schmid, & Hummel, 2019).

Using wearable devices in upper limb intervention provides several advantages over traditional rehabilitation by being portable, inexpensive, and flexible (Bonato, 2005; Fong & Chan, 2010; Wang, Markopoulos, Yu, Chen, & Timmermans, 2017). In such cases, wearable devices are electronic gadgets worn by users to capture or track biometric information related to health and fitness (Huaroto, Suarez, Krebs, Marasco, & Vela, 2019). In addition, the wearable device offers an opportunity for independent training by providing the end-user with augmented feedback, which is crucial for motor retraining (Wang et al., 2017). Although the clinical application of wearable technology in upper limb rehabilitation among the stroke population is relatively new, emerging research has shown promising results (Da-Silva et al., 2019; Lin et al., 2018; Wei, Fong, Chung, Cheung, & Chow, 2019; Whitford, Schearer, & Rowlett, 2020). In previous studies, a wearable device was used as an accelerometer to monitor

arm movement (Da-Silva et al., 2019; Wei et al., 2019; Whitford et al., 2020), providing external cues to prompt individuals to use their impaired arms in their daily routines (Da-Silva et al., 2019; Wei et al., 2019). A systematic review by Wang et al. (2017) highlighted that wearable device should support interactive therapy, which can be delivered through virtual reality and telerehabilitation, with the users receiving interactive stimulation through real-time visual and auditory feedback, thus enhancing their enjoyment during training (Lee, Park, & Park, 2019; Weiss et al., 2006). However, this feature of interactive therapy was generally absent in the studies mentioned above (Da-Silva et al., 2019; Wei et al., 2019; Whitford et al., 2020).

In addition to having an accelerometer and providing external cues, this study's proposed wristwatch (wearable device) had two enhanced functions: the addition of a gyroscope sensor and the integration of that sensor with an interactive telerehabilitation application. Indeed, inertial sensors such as accelerometers and gyroscopes are commonly used in wearable devices to capture human motion (Zhou, Stone, Hu, & Harris, 2008). An accelerometer is a sensor that measures linear acceleration along one or several directions by turning kinetic movement into a digital measurement (Aroganam, Manivannan, & Harrison, 2019; Yang & Hsu, 2010). In contrast, a gyroscope measures angular acceleration exclusively and is particularly useful for measuring orientation and projection involving angles, such as range of motion (ROM) (Aroganam et al., 2019; Passaro, Cuccovillo, Vaiani, De Carlo, & Campanella, 2017). Aroganam et al. (2019) highlighted that combining an accelerometer and a gyroscope helps to filter errors and increase accuracy in measuring angles. Unlike previous studies (Da-Silva et al., 2019; Wei et al., 2019; Whitford et al., 2020), this study's proposed wristwatch featured gyroscope and accelerometer sensors to accurately measure the arm's ROM.

Another enhancement of the proposed wristwatch was that it could be integrated with a telerehabilitation application (app) to offer interactive therapy. The wristwatch was linked to an app downloaded onto the participants' mobile devices, enabling the participants to view and perform the prescribed exercises while wearing the wristwatch. The sensors in the wristwatch captured the wearer's arm movements, while the mobile device, such as a smartphone, displayed a moving bar indicating the real-time range of motion of the participant's arm. This ROM angle display from the mobile device gave the user concurrent feedback on his or her performance and showed the targeted angle, motivating the user to aim for it. At the therapist's side, the therapist could remotely monitor the number of completed exercise sessions once the participants have done. The proposed wristwatch provided multimodal augmented feedback through its reminder (auditory and vibrotactile) and telerehabilitation (visual and auditory) features. Multimodal augmented feedback has been considered especially effective in motor learning because the human brain processes information better and quicker if feedback is presented from different modalities simultaneously (Moinuddin, Goel, & Sethi, 2021).

Before evaluating the clinical application of the proposed wristwatch, it was paramount to investigate its usability from the user's perspective. Redstrom (2006) highlighted that the lack of end-user involvement in the design process of such items as interactive systems might risk losing users' acceptance and approval. For a wearable device to be successfully incorporated into clinical trials, the users must be willing to wear and engage with it over a sustained period (Liang et al., 2018). Previous studies have confirmed that product usability is crucial to users' acceptance of a device (Mercer et al., 2016; Wen, Zhang, & Lei, 2017). According to the International Organization for Standardization (Usability Partners, 2022), usability refers to a product's effectiveness, efficiency, and user satisfaction rating in a specific environment for a particular purpose. Effectiveness is defined as the accuracy and completeness of a goal achieved by the product; efficiency refers to the effort required by the

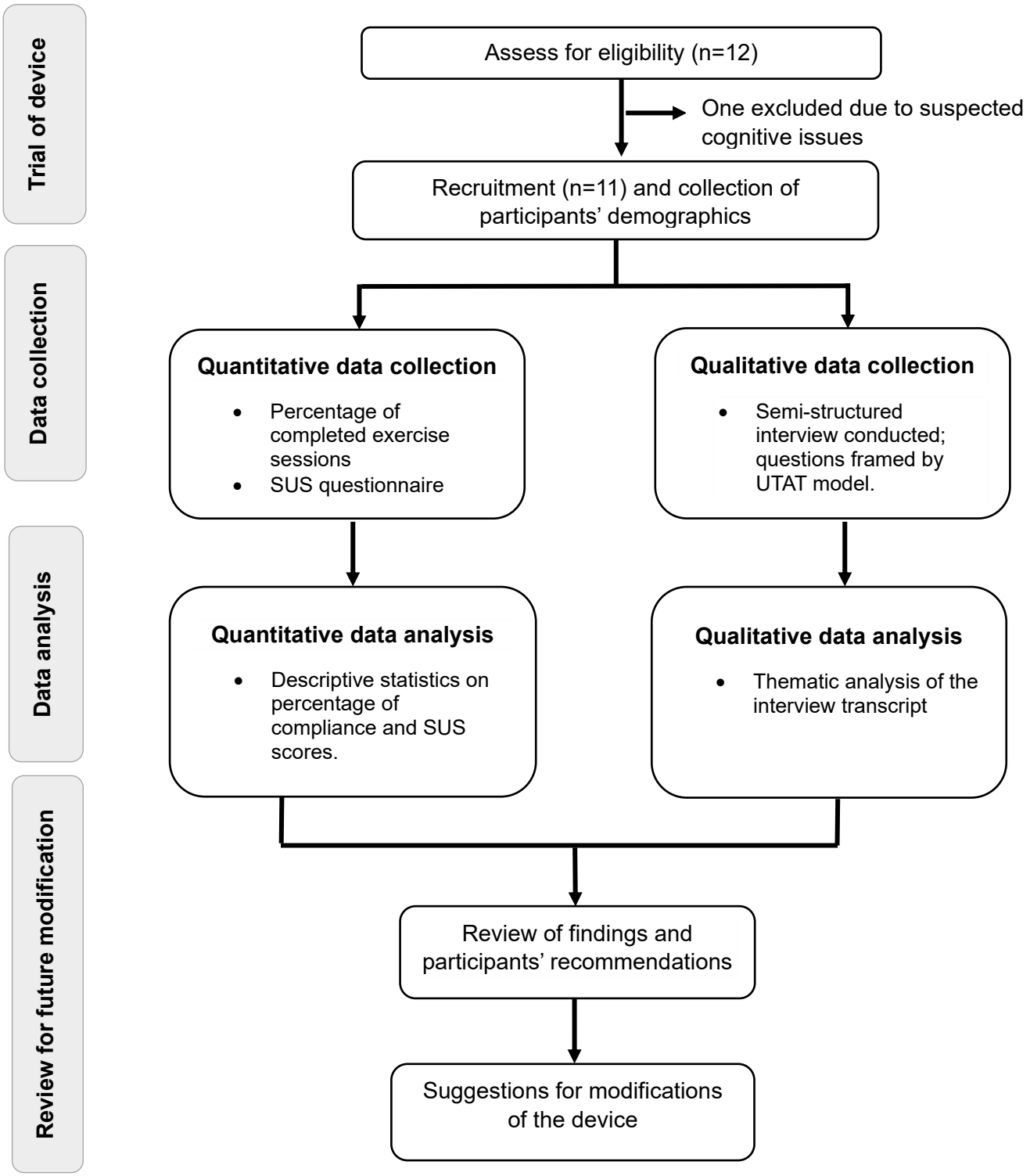
user to complete a specific task with the product, and satisfaction is the comfort and acceptability of the product (Liang et al., 2018).

To our knowledge, usability studies in wearable devices are rare; previous research on wearable technology has focused primarily on clinical validity (Liang et al., 2018; Rosenberger, Buman, Haskell, McConnell, & Carstensen, 2016). Keogh, Dorn, Walsh, Calvo, and Caulfield (2020) highlighted that it is essential to investigate the users' experiences on wearable devices. An understanding of users' perspectives will aid in the design of a wearable device that is useful and readily accepted by the users. Therefore, this study explored the usability of a wearable device as a wristwatch for home-based upper limb telerehabilitation for persons with stroke. Uncovering participants' experiences using this device should give valuable insights into improving its features for future clinical trials. This study sought to identify three main aspects of the proposed wristwatch: (1) its functions and features —specifically, which aspects the users valued and which ones they disliked; (2) its usability and acceptability, according to the participants; and (3) its features that required further modification.

4.3 Method

A mixed-methods exploratory study was conducted. Such an approach takes advantage of both quantitative and qualitative data to provide a complete panorama of the usability of the device's application as well as the users' attitudes and perceptions (Weichbroth, 2019). The COREQ (consolidated criteria for reporting qualitative research) checklist (Tong, Sainsbury, & Craig, 2007) was used to guide the qualitative approach in this study. Figure 4-1 presents a summary of the overall study design.

Figure 4-1: Summary of the overall study design



4.3.1 Recruitment

This study was conducted in Hong Kong. The research team contacted potential stroke participants from the community via phone and asked if they were interested in participating in the study. These participants were from a contact pool who joined previous research with the research team and had consented to be contacted again for future research. During a screening visit, they were screened using the selection criteria listed in Table 4-1. Then, they underwent an initial assessment by a licensed occupational therapist to evaluate their upper limb function. The study's details were explained to the participants using study information sheets. Written consent was obtained before recruitment. Participants were informed that they could withdraw from the study at any time. Furthermore, if a participant withdrew from the study, any data collected concerning the participant would not be analyzed unless the participant had given consent.

A purposive sampling method was used to identify and select individuals who were knowledgeable about or experienced with the phenomena of interest (Creswell & Clark, 2011). The participants were stratified according to their upper limb severity level, as determined by the Functional Test of Hemiplegic Upper extremity (FTHUE) (Wilson, Baker, & Craddock, 1984), and their age to gain richer insight into their experience with various characteristics. This study referenced the age classification (young: <48, middle-aged: 48-63, and older persons: >63) described by Lin et al. (2020).

Table 4 -1: Selection criteria of the study

Inclusion criteria: 1. age ≥ 18 years 2. unilateral hemiparesis 3. time of stroke onset ≥ three months 4. able to understand verbal instructions and follow 2 step commands 5. hemiplegic upper limb with FTHUE ≥ score of 3 6. score on modified Ashworth Scale (MAS) ≤ 2 7. no complaints of excessive pain and swelling over the hemiplegic arm
Exclusion criteria: 1. participant in an experimental drug study 2. cognitive or communication difficulties which would inhibit the person in the interview or use of the device 3. had botulinum toxin (Botox) injection in the previous three months with reference from previous studies (Chen et al., 2020; Wei et al., 2019), so that the treatment effect would not be influenced by the effect of botulinum toxin 4. other significant upper limb impairments, i.e., fixed contractures, frozen shoulder 5. a diagnosis which would interfere with the use of the device, i.e., visual impairment

As this was an exploratory study, a power calculation for the sample size was not conducted. Nonetheless, this study aimed to recruit 12 participants based on the recommendation by Julious (2005) for a pilot study. This study (HSEARS20220204001) was approved by the ethics committee of the Hong Kong Polytechnic University before its commencement, and the principles of non-maleficence, autonomy, and confidentiality were strictly followed.

4.3.2 Study procedures

The participants were each given a wristwatch (i.e., the study's wearable device) and then underwent home-based telerehabilitation for at least two weeks. The 2-week trial ensured that the participants had sufficient exposure to using the device and telerehabilitation application to share their user experience. An occupational therapist trained the participants to use the watch and connect it to a telerehabilitation application (app) that was downloaded onto their mobile devices. During the training, the therapist prescribed and taught the participants the appropriate exercises, based on the severity of their hemiplegic arm, using the telerehabilitation app. The therapist then discussed with the participants their daily schedules and recommended an exercise schedule for each individual. Finally, the therapist set a reminder interval provided by the watch, according to the agreed-upon exercise schedule. The participants were instructed to wear the watch for at least three hours a day and to follow the exercise schedule for at least three days a week. A typical exercise schedule for the participants was 30 minutes per session, two to three times a day.

4.3.3 The wearable device

The proposed wristwatch, 5cm x 3.5cm x 1.5cm, weighs 70g and has an accelerometer and gyroscope sensors. It has a rechargeable battery which allows 72 hours of continuous use. In addition, it had a Bluetooth function to allow a connection with a mobile device, such as a smartphone or tablet, to access the telerehabilitation app that had been downloaded onto the mobile device. Two web pages are designed, one for therapists to set the exercise parameters and remotely monitor the participant's movement data and another for patient use.

The wristwatch [Figure 4-2 and 4-3(a) and 4-3(b)] provided augmented feedback for training and activity tracking through three mechanisms:

1. Reminder function: The wristwatch emits a vibration and sound signal to remind the wearer to do the prescribed exercises. This emitted signal continued until the wearer pressed the acknowledgement button and performed the prescribed exercises. The reminder interval was predetermined and adjusted by the therapist.
2. Videos on prescribed exercises: Once the wristwatch was connected to the telerehabilitation app on the participants' mobile devices, they could watch videos of prescribed exercises and perform them. The wristwatch sensors detected and recorded the degree of range of motion as the participants moved their arms. From the telerehabilitation app, the participants received concurrent and terminal feedback on their movements during their exercise sessions.
3. Therapists' remote access to and evaluation of the participants' arm movement data: Data captured by the wristwatch for a participant's ROM angles and exercise sessions were uploaded to an encrypted cloud server, from which the therapist could remotely access and evaluate the patient's data.

Figure 4 -2: The wearable device and the telerehabilitation app

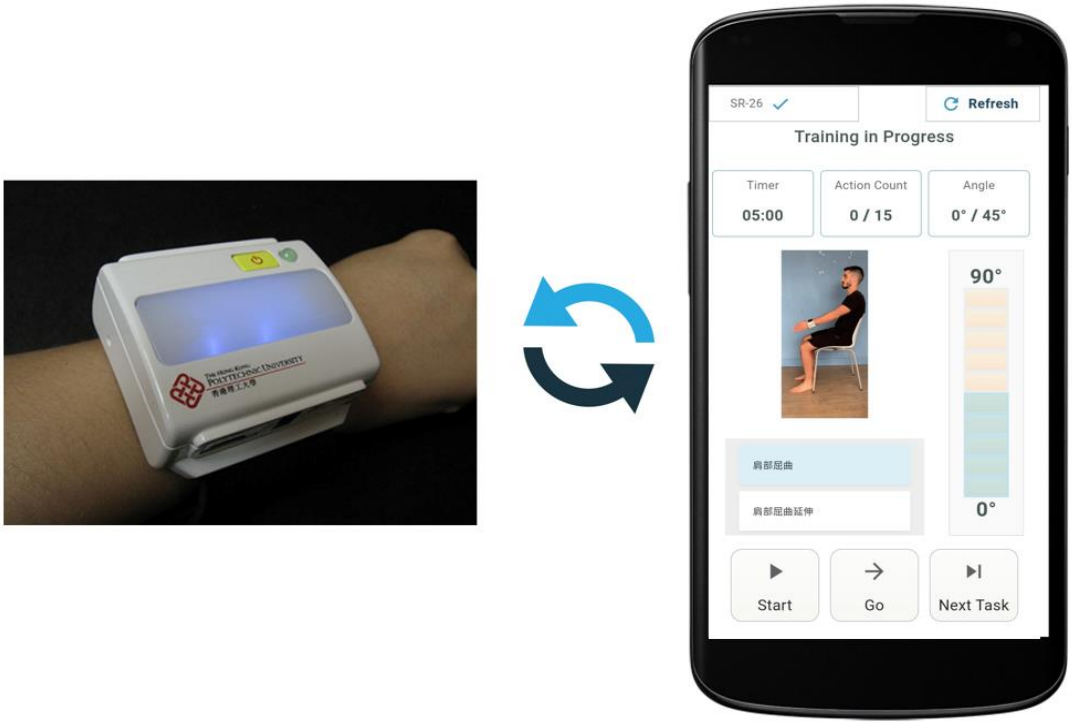


Figure 4 -3 (a): Participant's view

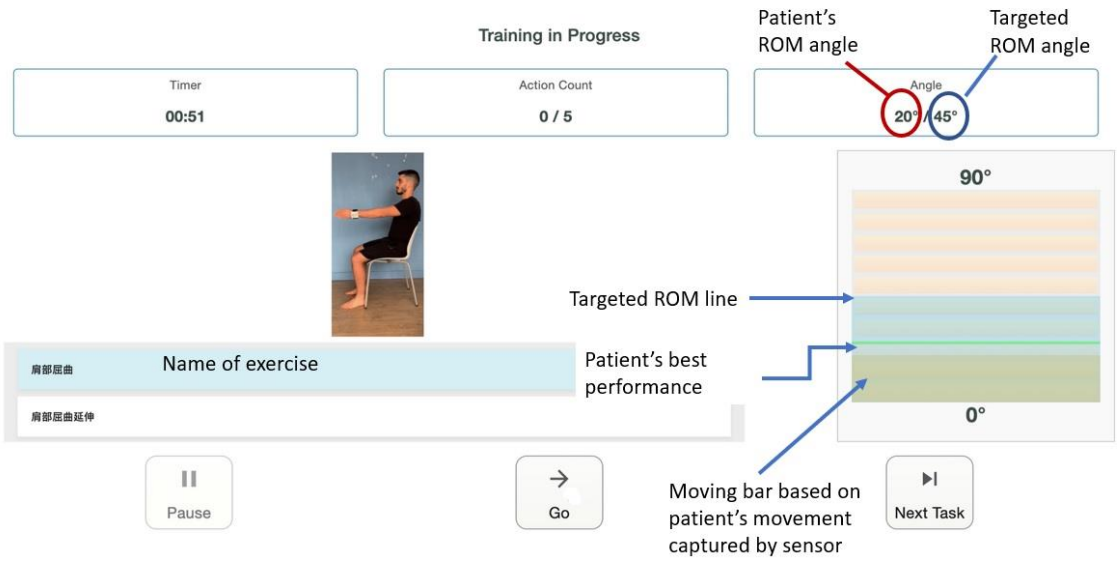
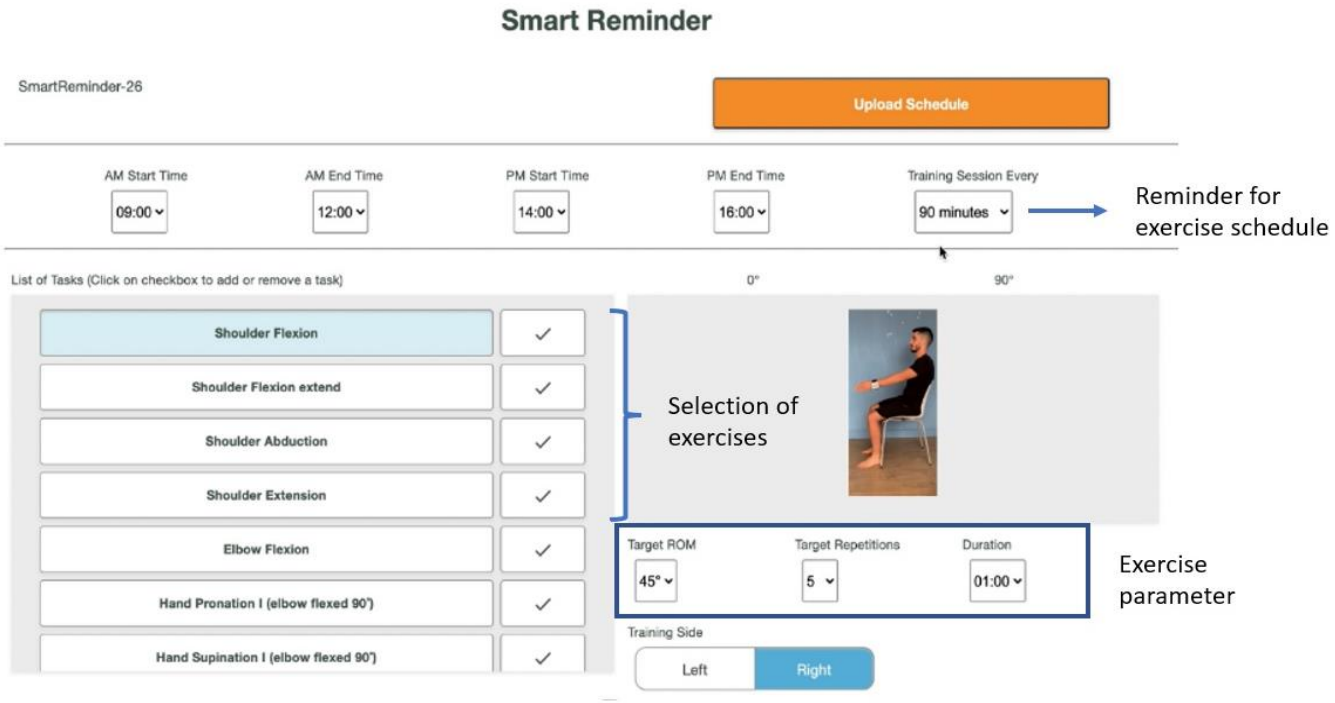
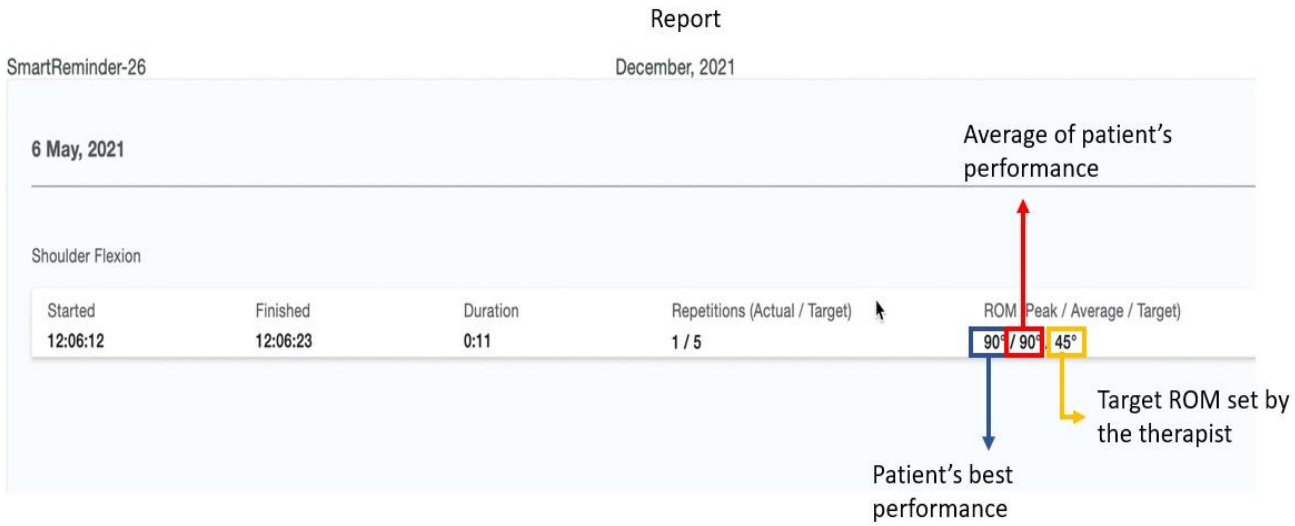


Figure 4 -3 (b): Webpage 1- Exercise prescription page



Webpage 2- Report



4.3.4 Data collection

After the trial period, quantitative and qualitative data were collected to understand the participants' experiences using the wearable device.

Quantitative data. Brief demographics of the participants were collected in terms of their age, time of stroke onset, gender, functioning level of their hemiplegic upper limb, and previous experience in using a wearable device. The participants were asked to complete the System Usability Scale (SUS) questionnaire, which is a scale that measures the usability aspect of a device (Brooke, 1996). It consisted of a 10-item questionnaire with five response options for the respondents, ranging from 1 = strongly disagree to 5 = strongly agree, and resulted in a possible minimum score of 0 and a maximum score of 100. A score of 68 and above was considered to represent above-average usability (Brooke, 1996). In addition, this study assessed the level of acceptability of the device, using the SUS score as described by Bangor et al. (2008). An SUS score below 50 was considered not acceptable, a score of 50-70 was considered marginally acceptable, and a score above 70 was considered acceptable. Furthermore, to calculate the therapy compliance rate of each participant, the researcher reviewed the wristwatch-collected data on the person's number of completed exercise sessions. The compliance rate was defined as "high compliance" if the participant completed at least 80% of the prescribed exercise sessions and "low compliance" if the participant did less than 80% (Alexandre, Nordin, Hiebert, & Campello, 2002).

Qualitative data. The first author (ST) and a research assistant conducted semi-structured interviews with the study participants. This method allowed the interviews to be organized with predetermined, open-ended questions guided by the research objectives and other questions that emerged from the dialogue between the interviewers and interviewees (DiCicco-Bloom & Crabtree, 2006). The advantage of this method was that it allowed the interviews to be focused

on addressing research questions while also providing the flexibility to examine deeper issues raised (Cranen et al., 2011a). Each interview lasted for 30 minutes to an hour. All the interviews were conducted face-to-face at a place of the participant's preference (i.e., the participant's home or the university lab). Smith, Flowers, and Larkin (2009) emphasized the importance of choosing an appropriate environment for an interview where participants feel most comfortable and familiar; hence, two choices for the interview location were given. The interviews were conducted with the participants alone or accompanied by their caregivers. With each participant's consent, the interviews were audio-recorded.

The interview guide consisted of core questions on the participant's history of stroke, treatment, motivation for participating in the study, experience in using the wearable device, any changes he or she recommended, and intention to use the device in the future.

4.3.5 Data analyses

Descriptive statistics were calculated to determine the mean SUS score of the participants and the mean rate of their compliance (total completed exercise sessions/prescribed sessions). The SUS score for each participant was computed using the standard scoring methodology (Brooke, 1996).

All the interviews were transcribed verbatim. Two researchers (ST & PC) analyzed the transcripts using the six phases of thematic analysis proposed by Braun and Clarke (2006). Data were arranged according to a thematic framework built upon the constructs of the unified theory of acceptance and use of technology (UTAUT) model, which was used because it is robust and parsimonious in understanding the drivers of a user's intention to accept information communication technology (ICT) (Venkatesh, Morris, Davis, & Davis, 2003). One key strength is that it can account for 70% of the variance in usage intention, in contrast to other models,

which routinely only explain approximately 40% of the variance (Venkatesh et al., 2003). This model described four constructs that could influence the user's attitude and behavioral intention to use the device: performance expectancy, effort expectancy, social influence, and facilitating conditions (Venkatesh et al., 2003). In each construct of the UTAUT, subthemes arising from the data were analyzed using an inductive process (Patton, 1990).

Participant identities were protected by coded identifiers to ensure confidentiality (Ho, Chiang, & Ku, 2015; Ryan, Coughlan, & Cronin, 2007). Documents with the participants' names and code numbers were kept in different locations under lock and key. All research data was to be discarded three years after study completion, with any documents that could reveal the participants' identities to be shredded.

4.3.6 Rigor and trustworthiness

Specific strategies were applied to ensure the trustworthiness of the qualitative data. First, investigator triangulation was used, with each interview being coded and analyzed separately by two researchers (Bernal-Utrera et al., 2021; Denzin, 2010). After that, a team meeting was conducted to compare and identify the overlapping themes and subthemes. Any differences were resolved with a third researcher, as needed. Researcher reflexivity was encouraged by maintaining a reflexive journal (Tufford & Newman, 2010). In addition to the reflexive journal, a researcher positionality map was also drawn to reflect how the researchers' positions impacted the analysis, knowledge production, and transparency (Goldberg & Allen, 2015; Hayfield & Huxley, 2015).

4.4 Results

Twelve participants from the community in Hong Kong were screened for eligibility to participate in the study. Eleven participants were recruited for the study. One participant did not meet the inclusion criteria due to suspected underlying cognitive difficulties influencing the person's learning ability to use the device. This study stratified the recruited participants into different age groups and levels of hemiplegic upper-limb functioning. The participants' ages ranged from 31 to 68 years, with a mean age of 56.5. Forty-two percent of the participants had a higher-functioning upper limb, and 58% had a lower-functioning upper limb. As the participants were recruited from the community, they all had experienced chronic stroke onset more than a year previously. All except one participant had no prior experience using a wearable device. Most participants (i.e., 9 out of 11) were no longer receiving outpatient rehabilitation during the study period. Table 4-2 outline the demographic characteristics of the participants.

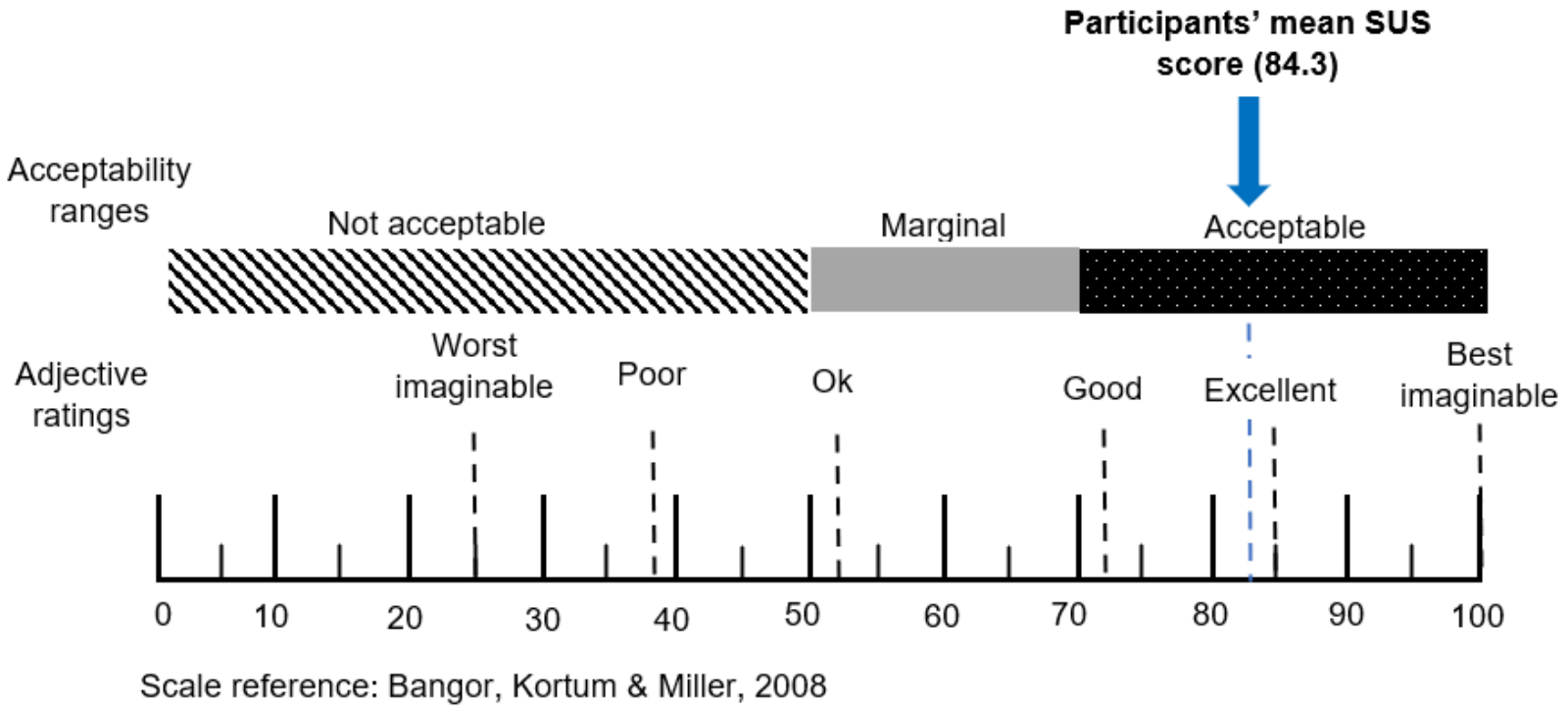
4.4.1 Quantitative results

Figure 4.4 illustrates the acceptability and adjective rating ranges of the participants' mean system usability scale score. The participants' mean SUS score for the wristwatch was 84.3 (12.3) out of a total score of 100, indicating an "above average" usability score (40) and an "excellent" acceptability level (Bangor et al., 2008). Regarding the treatment compliance rate, the mean compliance rate among the participants was 91%, indicating a "high compliance" rate as defined by Alexandre et al. (2002).

Table 4-2: Characteristics of the participants

Demographics , (n=11)	
Gender (n)	
Female	7
Male	4
Age (years)	
Years (mean± SD)	55.9 (11.1)
Young (<48 years old)	2
Middle aged (48-63 years old)	5
Older (>63 years old)	4
Time of stroke onset (years)	
Years (mean± SD)	6.3 (3.1)
> 1 year to 5 years	4
> 5 years	7
Upper limb severity, FTHUE (levels)	
FTHUE: 3 to 5 (low functioning)	7
FTHUE: 6 to 7 (high functioning)	4
Experience with wearable device(s)	
Yes	1
No	10
Accompanied during interview	
Yes	4
No	7

Figure 4- 4: The acceptability and adjective rating ranges of the participants' mean system usability scale score



4.4.2 Qualitative results

The themes and subthemes arising from the interviews were structured according to the constructs that form the thematic framework of the UTAUT model: (1) performance expectancy, (2) effort expectancy, (3) social influence, and (4) facilitating conditions, to which we added a fifth theme: (5) Intention to use. An overview of all the themes and subthemes is presented in Figure 4.5. Most participants related their experiences using the proposed wearable device to the constructs of performance expectancy, effort expectancy, and facilitating conditions. Fewer subthemes emerged from the construct of social influence.

4.4.2.1 Performance expectancy. Performance expectancy refers to the degree to which the participants believed using the device would improve their health outcomes (Cranen et al., 2011a; Venkatesh et al., 2003). All the participants expressed confidence in the proposed device's performance expectancy (theme/construct) through their positive perceptions of (a) its usefulness and (b) the physical improvements they experienced (subthemes).

Perceived usefulness. Participants found the wristwatch useful for creating health benefits and establishing an exercise routine. "Every night I want to do [it], as I think it will be useful for my hand, and I can control my hand as my hand will tremor," one female participant reported (P11). Some participants commented that the reminder function of the device established an exercise routine for them. A female participant (P5) shared, "It is like a reminder to me, as people are lazy like you paid to do exercise…. like attending a class… it gives the motivation for me to do [it]." Another female participant (P9) also mentioned that she could establish an exercise routine using the proposed device during the trial and had the autonomy to exercise independently without waiting for her weekly physiotherapy visit.

Perceived physical improvements. Most participants reported physical improvements in their hemiplegic limbs after using the wristwatch, such as increased upper and lower limb strength and reduced upper limb pain. One participant (P7) reported improvement in his shoulder strength, whereas another female participant (P11) indicated that after several exercises, she experienced reduced pain when she lifted her arm, "in the beginning, when I lifted my arm, I felt a bit [of] pain like the tendon stretched. Then after that, it is better."

4.4.2.2 Effort expectancy.

The effort expectancy theme/construct is defined as the degree of ease the user associates with using the device (Cranen et al., 2011a; Venkatesh et al., 2003). All participants unanimously shared that the device was user-friendly and easy to use. In addition, some participants found it convenient to use because it allowed them flexibility in the location and time when they used it. Nevertheless, for this construct, the participants highlighted two main challenges: technical issues and the wearability of the device.

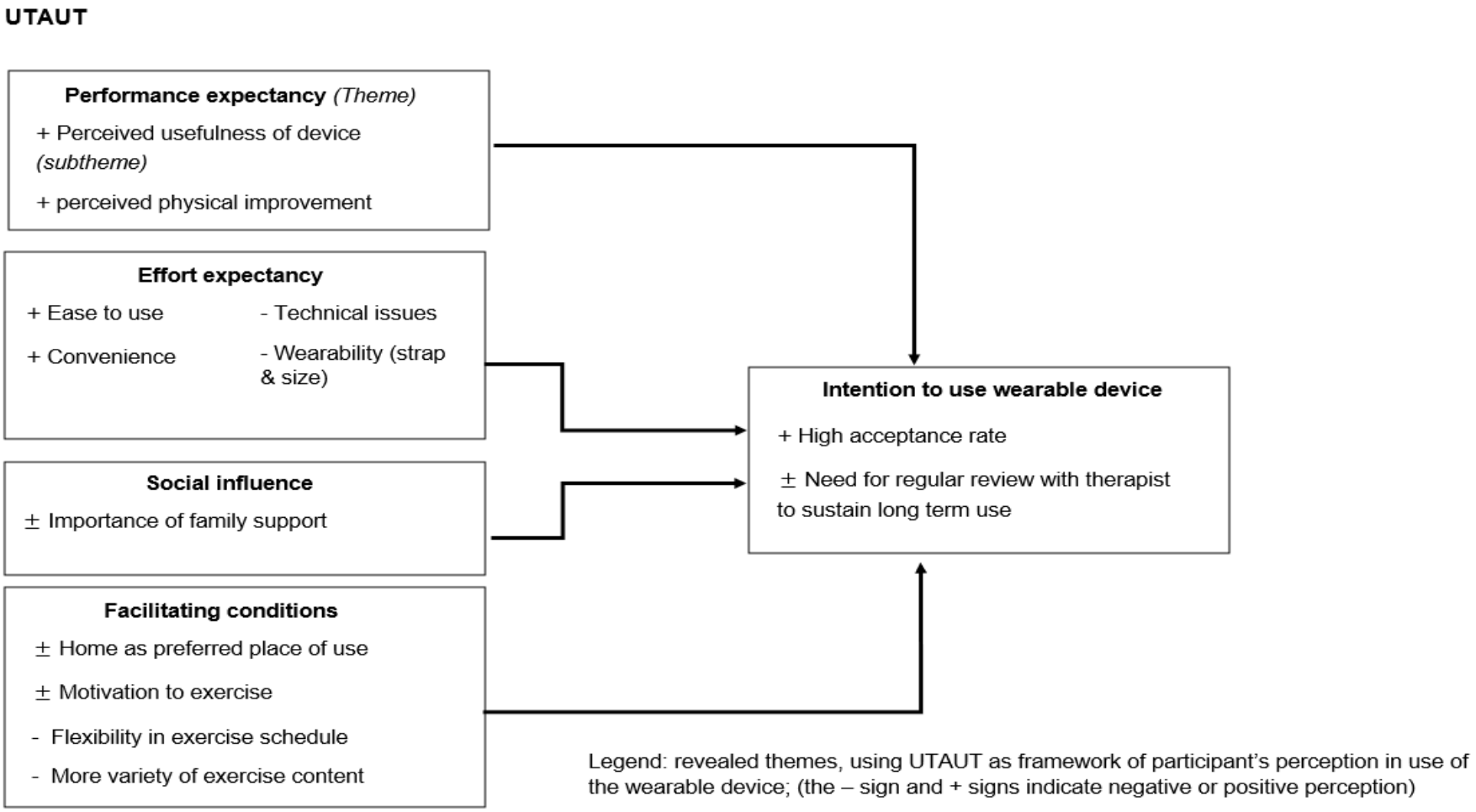
Ease and convenience of use. The study participants viewed the wristwatch's user interface design as simple and easy to learn. According to the participants, the exercise videos were easy to follow, and operating the watch and telerehabilitation system was simple. Several participants used terms such as "easy to use," "user friendly," "easy to handle," and "not very complicated" to describe their experiences in using the device. Furthermore, some participants appreciated the device's convenience in terms of the flexibility to use it at a preferred location and time. Given the high ownership of smartphones globally (Moral-Munoz, Zhang, Cobo, Herrera-Viedma, & Kaber, 2021), one unique feature of this device is its ability to integrate with the smartphone to offer a telerehabilitation experience. The portability of the phone allowed the participants to use the device at their preferred location with minimum set-up

required. A male participant (P7) highlighted this aspect, saying that the "phone is very convenient, everyone has a phone, the phone is easy to operate."

Wearability issues. Gemperle, Kasabach, Stivoric, Bauer, and Martin (1998) described wearability as the interaction between a wearable device and the human body. All participants stressed that the straps of the proposed wristwatch could be improved by changing the straps' material and attachment methods. Donning the watch was difficult for most participants, especially one-handedly, and two participants required assistance from their caregivers. For instance, female participants P3 & P5 commented that: "the strap is too thick, it is hard to wear, single hand it was difficult to wear " (P3); "for the strap, I think the hole too small, need to thread it. Basically, we all are one-handed ….if one of my hands has [a] problem, threading it will be difficult." Some participants also reported discomfort in wearing the watch for very long in the hot and humid weather due to the nonbreathable strap material. Another wearability issue the participants raised was the wristwatch size, which several felt was too bulky. "It is very bulky if you go out, others will notice it and wonder what it is?" commented a participant (P11). Participants expressed that the watch's size affected their intention to wear it outdoors, as it might appear too obtrusive and attract unnecessary attention.

Technical issues. Nearly all participants reported facing minor technical issues when using the proposed watch. Common technical problems included system hangs, short battery lifespan, and slow response time from the system. One male participant (P1) reported a delayed response from the telerehabilitation screen as he moved his arm with the wearable sensors. Nevertheless, all participants could troubleshoot and resolve these issues independently or with assistance from others (i.e., their caregivers and the researchers). None required a replacement of the device during the trial period.

Figure 4- 5: The themes and subthemes of qualitative findings



4.4.2.3 Social influence. The social influence construct refers to the degree to which an individual perceives that their significant others' views on the device will influence their usage (Venkatesh et al., 2003). The study participants held differing opinions on the importance of their families' and friends' views in influencing their use of the device. Slightly more than half of the participants did not consider the opinions of their families and friends to be significant in affecting their intention to use the proposed wristwatch. One male participant (P10) said: "…not really (refers to family members' view), you want to try on your own. So no difference." In contrast, other participants valued the opinions of their family members and felt that family support was essential to encourage them to use it.

4.4.2.4 Facilitating conditions. The facilitating conditions construct embodied three different constructs: perceived behavioral control, facilitating conditions (i.e., objective factors in the environment), and compatibility (Cranen et al., 2011a; Venkatesh et al., 2003). These constructs captured the users' perceptions of their ability to perform the behavior and to measure the degree to which the system aligned with their existing values, previous experience, and current needs (Venkatesh et al., 2003). Four subthemes emerged from this construct: physical location, motivational factor, flexibility in exercise schedule, and exercise content.

Physical location. All participants preferred to use the proposed wristwatch at home, which they perceived as a conducive environment because it provided them with privacy and physical space to perform their exercises. Some expressed hesitancy to wear the device outdoors, as they were concerned about others' perceptions, primarily due to its obtrusiveness and aesthetics and the lack of a suitable place. For instance, this reservation was expressed by a female participant (P3): "if I bring outside and do [it], I [am] scared it will scare my friends and relatives… it will beep … then others may not understand what happened." While the home

environment offered a conducive place for the participants, their use of the device and exercise compliance were limited by their duration at home. Participants who had several outdoor activities in their daily routine expressed difficulty finding time to do the exercises.

Motivation to exercise. Several participants highlighted a "laziness tendency" within themselves regarding the construct of perceived behavioral control, and they perhaps were not self-disciplined enough to perform the exercises if left alone. However, most participants stressed that the wristwatch's remote monitoring and reminder features motivated them to exercise. The telerehabilitation system connected to the watch allowed the therapist to remotely monitor the participants' progress. This function was highly valued by the participants and created a source of motivation for them. One female participant (P2) pointed out, "you can check from your computer my progress. If I am too lazy, you can call me, "why you didn't do?"... this gives the patient encouragement…. " Another male participant (P7) also emphasized: "I think it is good to us patients, it is useful, it motivates me and monitors because people are lazy… sometime we don't want to do …" Moreover, some participants appreciated the device's reminder function and were motivated to exercise. As one female participant (P4) mentioned, she felt compelled to do the exercises when reminded by the wristwatch: "initially I don't bother [to do] it…. but it is very persistent in calling me to do so I do ...If there is no watch, my motivation to do exercise will not be great….".

Despite these features, some participants still lacked the motivation to exercise. One participant (P6) attributed his lack of motivation to his character and recommended a reward system using music or a point system as an external motivator to celebrate a user's success if he had achieved the desired goal.

Flexibility in exercise schedule. Some participants perceived flexibility in their exercise schedule to be a necessity. They preferred to exercise at their preferred time, which might not

always coincide with their agreed-upon schedule with the therapist. Although the proposed device allowed such flexibility, the device's reminder system created some restrictions because the alarm would ring at the previously scheduled time set by the therapist. Unfortunately, the participants did not have access to adjust the reminder times, so instead, they did not use the reminder function and switched on the device only when they wanted to use it.

Exercise content. Some participants requested more variety of exercise content in the telerehabilitation system in order to sustain their long-term engagement. Whenever they made physical improvements, they expected the difficulty level of the exercises to be adapted to their new abilities to provide the "right amount of challenge."

4.4.2.5 Intention to use. When asked about their intention to use the device in the future, all participants unanimously indicated their keenness to use it. Nevertheless, to facilitate long-term usage, some participants requested an interim review with the therapist on their progress and the opportunity to adapt the prescribed exercises throughout the intervention. In their reviews with the therapist, they wanted to discuss adjusting the device's external prompts and adapting the exercises' difficulty level according to their upper limb's progress. In addition, some wished to see their progress and self-monitor it from the telerehabilitation system. With that ability, they could feel even more motivated to pursue continuous improvement.

4.4.3 Suggested changes to the device

This study adopted a human-centered design approach by focusing on the user's needs and requirements (Rodgers, Alon, Pai, & Conroy, 2019). Besides exploring the device's usability and the users' experiences with the device, we sought to identify the features of the proposed device that required modification. During the interviews, the participants were asked

to suggest any changes they would like to recommend for the device. The top five changes proposed by the participants are: (a) changing to the strap, (b) reducing the size of the device, (c) more exercise variety, (d) reducing the weight of the device, and (e) resolving technical issues.

The suggested changes were consistent with the challenges highlighted by the participants. The participants emphasized the need to improve the wearability of the device in terms of the straps and size. Participants wanted the proposed wristwatch to be easy to wear and more comfortable (i.e., with a more breathable strap material). Some referred to their existing watches, which used silicone straps, as an example. In addition, the participants desired a more unobtrusive and smaller device to wear outdoors. Finally, to prevent boredom and encourage long-term use, they felt that the exercise content needed to be varied and graded in terms of the level of challenge.

4.5. Discussion

This study explored the usability of a wristwatch to provide home-based upper limb telerehabilitation for persons with stroke. The study's quantitative and qualitative results demonstrated a positive experience using the proposed wearable device. The participant's high SUS scores and compliance rates implied that the proposed wearable device and telerehabilitation program were well received. In addition, the quantitative results were congruent with the participants' qualitative accounts, as was highlighted in the subthemes, such as the perceived usefulness and ease of use of the device and the participants' perceived physical improvements and enhanced motivation to exercise. Furthermore, despite the technical and wearability challenges, all participants unanimously indicated their intention to use the device again. This finding echoed the observation made by Keogh et al. (2020) that

participants were willing to accept minor annoyances in a device that they perceived to be useful and beneficial.

This study proposes three possible explanations for the excellent usability scores and positive user experiences with the proposed device. First, the actual experience of using the wearable device appeared to debunk any preconceived fears concerning the device's efficacy, thus underscoring Kairy and colleagues' (2013) emphasis on the importance of allowing users to use the technology when evaluating it, on the assumption that users who have yet to experience an innovative technology might have an inaccurate view of it (Cranen, Veld, Ijzerman, & Vollenbroek-Hutten, 2011b). Indeed, several studies have shown that participants changed their perception of using a home-based technology such as telemedicine more positively after using it (Cranen et al., 2011b; Demiris, Speedie, & Finkelstein, 2001; Finkelstein et al., 2004).

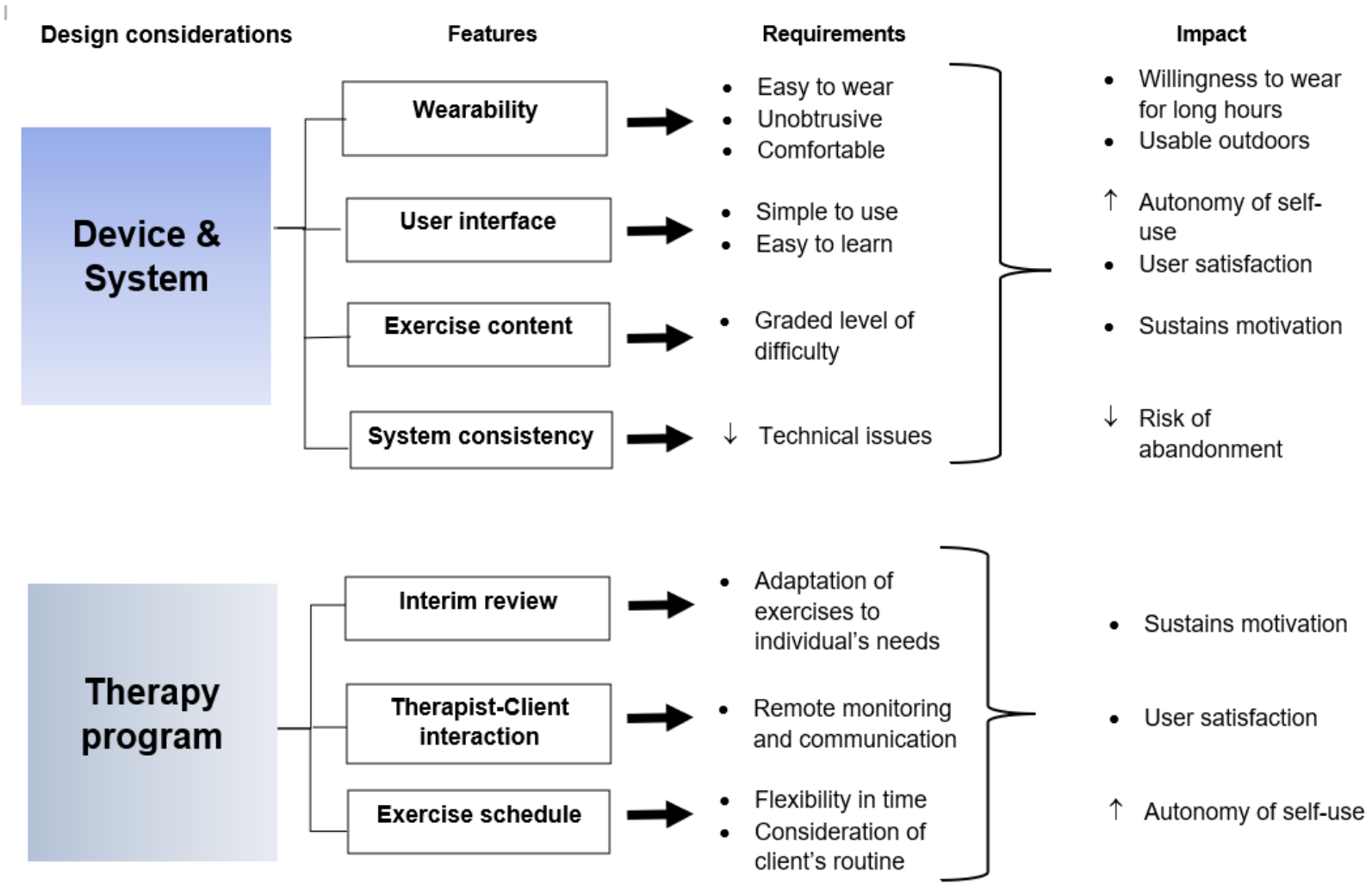
Second, despite having faced technical issues when using the device, participants could resolve the problems independently or receive timely support from their carers or the researcher. For instance, some participants contacted the researcher during the trial regarding technical issues, and the researcher advised them accordingly through videos and visuals via text messaging. Ultimately, then, those issues did not persist in affecting their user experience. Hanson, Calhoun, and Smith (2009) highlighted the importance of maintaining a positive user experience in the early adoption phase of a technology system to avoid disappointments with its efficacy and efficiency. One solution was providing timely and personalized support and troubleshooting to resolve potential technical issues that arose with the new system.

Lastly, one reason was that the positive experience was influenced by the effect of Gartner hype cycle. The hype cycle introduced by Gartner Inc., a technology research and consulting firm, explains the general path of user expectations when new technology is

introduced (Steinert & Leifer, 2010). In the initial process of introducing a new technology, the hype cycle indicates a peak of "inflated expectations," followed by a "trough of disillusionment" when unrealistic expectations are not met (Fenn & Raskino, 2008). This phenomenon might be reflected in a previous study by Hanson et al. (2009), who explored the views of first-time and experienced users of a telemedicine service. Those researchers found differing patterns of fluctuating high expectations and disillusionment among two groups of participants. First-time users were more likely to shift their expectations of the telemedicine service positively, whereas the experienced users changed their attitudes in a more negative direction (Hanson et al., 2009). Most participants in this study were first-time users of this device, and their positive experience might have reflected a degree of "overenthusiasm," as indicated in the Gartner hype cycle.

Figure 4-6 summarises the participants' suggested design considerations for the proposed device and program. This study identified four considerations concerning the design of the wearable device: wearable factors, user interface, system performance consistency, and graded exercise content. Wearable factors—those that make the device easy to wear, unobtrusive, and comfortable—are emphasized and supported by previous studies (Cherry et al., 2017; Wang et al., 2017). Most persons with stroke have unilateral hemiparesis, so the attachment method of the wearable device needs to support single-handed attachment and wearing, and the strap material should be comfortable enough to encourage wearing the device for a long duration. Furthermore, the device should be unobtrusive to avoid attracting unnecessary public attention and support outdoor use. Finally, the device's user interface should be simple and easy to learn to reduce the cognitive load of persons with stroke and support independent use. Our findings were in accord with those in previous studies—persons with stroke feel that home-based assistive technologies should be simple and easy to use to support self-management (Demain et al., 2013; Elnady, Mortenson, & Menon, 2018).

Figure 4- 6: Summary of the participants' suggested design considerations for the device and program



One critical challenge faced by our study participants was encountering technical issues when using the proposed device, a frequently highlighted problem in previous studies on using technology-based interventions (Chen et al., 2020; Cherry et al., 2017; Cranen et al., 2011a; Kairy et al., 2013). Unlike in the clinical setting, where the environment offers all the necessary technical support from professionals (Chen et al., 2020), home-conducted therapy requires the patients and their caregivers to navigate technical challenges firsthand. Thus, designing a device that performs consistently is imperative, as it minimizes the risk that users will lose confidence in its efficacy and abandon the device. The reliability and durability aspects of an assistive technology's performance are also considered significant predictors of its acceptance or abandonment by users (Phillips & Zhao, 1993). Repeated functional testing and adequate training in device use are methods to minimize technical issues during device implementation. In addition, timely technical support from the caregiver or researcher is pivotal to maintaining a positive user experience when using home-based technologies (Chen et al., 2020).

Last, when reporting on the design of the telerehabilitation system, our study participants underscored the importance of having a variety of exercises with a graded level of difficulty to sustain their engagement in the therapy. Like the participants in a previous study (Chen et al., 2020), our participants expected the prescribed exercises to change according to their hemiplegic upper limb's progress over time.

The study identified three considerations that should be followed when designing the therapy program: having an interim review, including therapist-client interactions, and ensuring flexibility in the exercise schedule. The study participants emphasized the importance of an interim progress review with the therapist because they desired an individualized treatment plan adapted to their own therapy needs. Previous studies also argued that customization of clinical intervention is crucial (Bernal-Utrera et al., 2021; Garber et al., 2011). In addition, therapist-client interactions and communication are critical elements for maintaining the

participants' motivation and engagement in a therapy program, especially in an unsupervised home setting. Our study participants appreciated the remote monitoring from the therapist because it motivated them to continue in the therapy program. This finding echoed the participants in the study by Bernal-Utrera et al. (2021), who indicated that having someone to care for them and monitor their clinical status was a positive factor in their telerehabilitation program.

Finally, an important advantage of the proposed device over traditional scheduled therapy was its flexibility, with the option to use it at various times and locations. Other studies have also documented the value of such an advantage with a telerehabilitation or telemedicine system (Chen et al., 2020; Cranen et al., 2011a; Kairy et al., 2013). Nonetheless, one caveat was that the reminder function from the proposed device required a fixed schedule which the participants could not modify on their own. Thus, to mitigate the study's issues, flexibility should be enhanced through regular communication between the therapist and client and should include the client's ability to adjust the reminder setting.

4.6 Strengths and limitations of the study

This study adopted a mixed-methods design to obtain a robust understanding of the usability and user experience of a wearable device with telerehabilitation features in persons with stroke. Participants were given at least two weeks to use the proposed device, thereby addressing a limitation from previous usability studies which failed to test their devices beyond 24 hours (Keogh et al., 2020). Furthermore, this study gathered end-user feedback that included recommendations for further modifications to the proposed device before conducting extensive clinical testing. This study also included a wide age range of participants (i.e., 31 to 68 years old) with varying levels of upper limb function to broaden our insight into the usability of the

proposed device, especially because a previous study had indicated that differences in expectations arose between young users and older ones (Johnson & Kent, 2007). An older-person-focused design might not meet the functionality requirements desired by young users (Johnson & Kent, 2007) and balancing the needs and interests of a broader range of users when designing such a device is paramount (Cheung, Or, So, & Tiwari, 2018).

There were some limitations to this study. Firstly, this was a usability study, further investigation of its effectiveness with a larger sample size using the wearable device for telerehabilitation is recommended. Secondly, all participants were in the chronic phase of stroke, and we did not explore the user experiences of persons with acute or subacute phases. A previous study (Sanders et al., 2020) indicated that subacute users might respond differently to a proposed treatment than chronic users. In addition, persons in the subacute stage of stroke might have relatively more untried therapy options available than those in the chronic phase and may prefer other interventions over the proposed home-based therapy using wearable technology (Sanders et al., 2020). Moreover, subacute, and acute stroke patients might have multiple medical and rehabilitation appointments that would increase their busyness and affect their commitment to and compliance with such research.

In addition, it was unclear whether the participants' positive reports about their experience were influenced by the Gartner hype cycle's effect or were authentic physical improvements the participants experienced. Further research can be conducted to evaluate the clinical effectiveness of this proposed device and objectively assess the participants' physical progress. Lastly, this study focused on the user experience of the wearable device (i.e. stroke survivors), the viewpoint of the healthcare providers was beyond its scope. Healthcare providers play a crucial role as advocates, hence future studies can be considered to explore their viewpoints.

4.7 Conclusion

This study's findings supported the usability of the proposed wearable device and showed that participants were satisfied with using it as a home-based upper limb telerehabilitation intervention. In addition, this study highlighted several fundamental considerations for designing such a wearable device and its accompanying telerehabilitation program for individuals with chronic stroke. These findings will aid developers in considering real challenges from the user's perspective and making improvements before conducting more extensive usability testing.

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Chapter 5: 'Smart Reminder': a Feasibility Pilot Study on the Effects of a Wearable Device Treatment on the Hemiplegic Upper Limb in Persons with Stroke

This chapter investigated the clinical effect of the novel wearable device, 'Smart Reminder' for home-based telerehabilitation for persons with stroke. This chapter was published by the author of this thesis as a feasibility pilot study in Journal of Telemedicine and Telecare in January 2024. The citation for this study was:

Toh, F. M., Lam, W. W., Gonzalez, P. C., & Fong, K. N. (2024). 'Smart reminder': A feasibility pilot study on the effects of a wearable device treatment on the hemiplegic upper limb in persons with stroke. *Journal of Telemedicine and Telecare*, 1357633x231222297. doi:10.1177/1357633x231222297

The manuscript, included below, has been formatted according to APA 6th to align with the thesis format. References are provided at the end of the thesis.

5.1 Abstract

Background: Emerging literature suggests that wearable devices offer a promising option for self-directed home-based upper limb training for persons with stroke. However, little research is available to explore integrating smartphone applications with wearable devices to provide upper limb telerehabilitation to stroke survivors at home. This study examined the feasibility and potential therapeutic effects of a wearable device integrated with a smartphone-based telerehabilitation system to provide upper limb rehabilitation to stroke survivors at home. **Methods:** Twelve stroke survivors from community support groups participated in a treatment consisting of 4-week telerehabilitation using a wearable device and 4-week conventional therapy successively in a single-blind, randomised crossover study. A 3-week washout period was administered between the two 4-week treatments. The primary outcome measures were the Fugl Meyer Assessment, the Action Research Arm Test, and the active range of motion of the upper limb. Secondary outcome measures included the Motor Activity Log and exercise adherence. **Results:** Results showed that the active ROM of participants' hemiplegic shoulder improved more significantly after four weeks of telerehabilitation with the wearable device than with conventional therapy. No significant differences were found in other outcome measures. **Conclusion:** A 4-week telerehabilitation programme using a wearable device improves the hemiplegic upper limb in community-dwelling stroke survivors and may be feasible as an effective intervention for self-directed upper limb rehabilitation at home.

Keywords- Home-based interventions, wearable technology, telerehabilitation, stroke, usability

The trial was registered on ClinicalTrial.gov (URL: http://www.clinicaltrials.gov) with the identifier NCT05878132.

5.2 Introduction

Upper limb paralysis is a common and crippling complication of stroke. Stroke survivors, caregivers, and healthcare professionals have highlighted the importance of upper limb rehabilitation (Pollock, St George, Fenton, & Firkins, 2012). Previous reviews (Pollock et al., 2014; Van Peppen et al., 2004) stressed that therapies involving intensive and task-specific practice have been proven effective in promoting recovery of the hemiplegic upper limb after stroke. However, such therapies can be resource-intensive if performed in person in the hospital. With the increasing demand for limited healthcare resources, the emphasis shifts from hospital-based rehabilitation to home-based self-directed training through empowering stroke survivors and their caregivers (Da-Silva et al., 2019; Fryer, Luker, McDonnell, & Hillier, 2016; Harris, Eng, Miller, & Dawson, 2009). Self-directed training conducted at home is preferred as it allows stroke survivors to practise their skills in their real-life environment for better skill transfer (Dobkin, 2017) and offers avenues for intensive practice of the affected arm while reducing the need for supervised therapy and travel to and fro healthcare facilities.

Recent technological interventions, for example, telerehabilitation (Asano et al., 2021) and wearable devices (Maceira-Elvira, Popa, Schmid, & Hummel, 2019), offer stroke survivors the avenue for autonomous repetitive practice, a beneficial alternative to conventional therapy. Wearable devices are electronic devices worn outside the human body to monitor users' activities without interrupting or restricting their movements (Parker, Powell, & Mawson, 2020; Rodgers, Alon, Pai, & Conroy, 2019). A prominent feature of wearable devices is the ability to provide augmented feedback to users, an active form of guiding patients in their daily self-directed training (Kim, Parnandi, Eva, & Schambra, 2022; Wang, Markopoulos, Yu, Chen, & Timmermans, 2017). Augmented feedback refers to information an external source provides, including visual, auditory, haptic, and multimodal feedback (Jakus, Stojmenova, Tomažič, & Sodnik, 2017; Moinuddin, Goel, & Sethi, 2021). This type of feedback serves as a useful

extrinsic prompt in motor training for some stroke survivors whose intrinsic feedback mechanisms (e.g., proprioceptive cues) are weakened or altered (Van Vliet & Wulf, 2006).

Emerging literature suggests that wearable devices may be a promising tool to enhance home-based training to promote hemiplegic upper limb function recovery in persons with stroke (Chae, Kim, Lee, & Park, 2020; Choudhury et al., 2020; Da-Silva et al., 2019; Palmcrantz, Pennati, Bergling, & Borg, 2020; Seim, Wolf, & Starner, 2021; Wei, Fong, Chung, Cheung, & Chow, 2018; Whitford, Schearer, & Rowlett, 2018). Five studies (Chae et al., 2020; Choudhury et al., 2020; Palmcrantz et al., 2020; Seim et al., 2021; Wei et al., 2018) revealed that the wearable devices group showed a more statistically significant improvement in the hemiplegic upper limb motor performance than those in the control group who received sham or conventional therapy. Two studies (Da-Silva et al., 2019; Whitford et al., 2018) found a similar improvement in the affected arm but did not reach statistical significance. These studies (Chae et al., 2020; Choudhury et al., 2020; Da-Silva et al., 2019; Palmcrantz et al., 2020; Seim et al., 2021; Wei et al., 2018; Whitford et al., 2018) applied wearable devices in different interventions, such as activity trackers, somatosensory stimulation, and accelerometry-based feedback.

A previous review by Wang and colleagues (2017) recommended that an interactive component is favourable in self-directed training using wearable devices because it increases the users' engagement and motivation. For instance, in telerehabilitation and virtual reality training, users receive interactive stimulation through real-time visual and auditory feedback, enhancing their enjoyment during training (Lee, Park, & Park, 2019; Weiss, Kizony, Feintuch, & Katz, 2006). This training mode provides users with an interactive exercise experience and is generally absent in previous wearable device studies mentioned above (Chae et al., 2020; Choudhury et al., 2020; Da-Silva et al., 2019; Palmcrantz et al., 2020; Seim et al., 2021; Wei et al., 2018; Whitford et al., 2018). Recent advances in smartphone technology offer

tremendous potential to be used in rehabilitation systems, and information can be transmitted to an encrypted cloud system for remote monitoring (Wang et al., 2017). Although some studies (Ballester et al., 2017; Wittmann et al., 2016) applied wearable devices in virtual reality training, none used smartphone technology as a more portable visual display (Toh, Fong, Gonzalez, & Tang, 2023a).

Given the high smartphone penetration worldwide (Laura, 2019), smartphone-based telerehabilitation has emerged and grown exponentially in the past decade (Moral-Munoz, Zhang, Cobo, Herrera-Viedma, & Kaber, 2021). To the best of our knowledge, there is little research exploring integrating smartphone software applications with wearable devices to provide upper limb training for stroke survivors at home. Therefore, we have developed a wearable device called 'Smart Reminder' that integrates with a smartphone's telerehabilitation application to provide multimodal feedback, the most effective type for promoting motor relearning (Moinuddin et al., 2021). This device offers auditory and vibrational prompts to remind stroke clients to exercise. It also connects to an application on the smartphone to allow patients to view prescribed exercises.

During the training session, the inertial sensors in the device capture the angles of the wearer's arm movement and provide real-time feedback on their performance. This real-time feedback motivates the user and provides the right level of challenge. Simultaneously, the movement data are uploaded to an encrypted cloud system for the therapist to monitor the user's progress remotely. In a previous usability study (Toh, Gonzalez, & Fong, 2023b), we demonstrated that stroke survivors received this proposed device well and stated that further investigation of its clinical validity was needed. Therefore, this study examined the feasibility and possible effects on hemiplegic upper limb recovery of using the 'Smart Reminder' wristwatch for upper limb telerehabilitation for community-dwelling stroke survivors at home using a smartphone.

5.3 Method

5.3.1 Participant and Study Design

A convenience sample of 12 participants was recruited from community stroke support groups in Hong Kong from August to December 2022. The investigators screened the eligibility of the participants according to the inclusion criteria: (1) age >18 years, (2) unilateral hemispherical involvement, (3) diagnosis of stroke with onset >3 months, (4) Functional test for upper extremity-Hong Kong version (FTHUE-HK) (Fong et al., 2004) score of 3 (maximum of 7), (5) no complaint of excessive pain and swelling over the hemiplegic arm, and (6) capable of giving informed consent. Participants were excluded if they were (1) participating in another similar form of experimental study during the same period, (2) had a history of botulinum toxin injection in the past three months, (3) had other significant upper limb impairment, i.e., fixed contractures, frozen shoulder, and severe arthritis, and (4) had a diagnosis that would interfere with device use, i.e. visual impairment, active cardiac problems, and palliative treatment. This study was approved by the Human Studies Committees of the Hong Kong Polytechnic University (HSEARS20220704001). The trial was registered on ClinicalTrial.gov (URL: http://www.clinicaltrials.gov) with the identifier NCT05878132. Informed consent forms were obtained from the participants. After completion of the study, the participants received a supermarket voucher as a token of appreciation.

This study was a single-blind, randomised, two-period crossover design. The CONSORT checklist (Schulz, Altman, & Moher, 2010) guided the study approach (see Supplementary 1). Figure 5.1 shows the overall study design. Participants were randomly assigned to Group 1 (WD-CT) or Group 2 (CT-WD) using a computer-generated random number sequence. Randomisation was stratified according to the participant's baseline upper limb severity. In Group 1 (WD-CT), participants received a 4-week telerehabilitation using the

wearable device called 'Smart Reminder' first, then conventional therapy after the crossover period. Group 2 (CT-WD) received a 4-week conventional treatment first, then the telerehabilitation using 'Smart Reminder' after the crossover. A three-week washout (no treatment) was administered between the two intervention periods. Based on previous stroke rehabilitation studies (Hijmans, Hale, Satherley, McMillan, & King, 2011; Sczesny-Kaiser et al., 2019) that used a one- to three-week washout period, a three-week washout period was assessed to be adequate to eliminate any carryover effects from the earlier treatment. Only assessors who conducted outcome measures on participants were blinded to treatment allocation. Masking in treatment allocation for therapists and participants was not feasible.

5.3.2 Wearable Device

The "Smart Reminder" is a wristwatch with the dimensions of 6.5 x 6.0 x 2.5 cm and weighs around 70g. It has an accelerometer and gyroscope sensors and uses a rechargeable battery with a recording capacity of up to 72 hours of continuous operation. The device is intelligently programmed to emit vibrations and audible signals to remind the wearer to perform the prescribed exercises. The wearer must press the acknowledgement button or complete the exercises to stop the emitted signals. The frequency of the signals is tailored and predetermined by the therapist using a web portal.

Furthermore, the device has a Bluetooth function that connects to a telerehabilitation application on smart devices such as smartphones or tablets for training (see Figure 5.2a). Through the telerehabilitation application, participants can see the prescribed exercise videos determined by the therapist and receive visual feedback on their performance (see Figure 5.2b). The types of exercises in the videos consist of shoulder, elbow, and forearm range-of-motion exercises. The in-built sensors in the wearable device detect and record a participant's range of

motion (ROM) and the number of completed repetitions for therapist evaluation. Subsequently, these kinematic data were uploaded to an encrypted web portal that allowed the therapist to evaluate and monitor remotely (see Figure 5.2c).

5.3.3 Interventions

In both groups, all participants underwent a 4-week telerehabilitation using the 'Smart Reminder'. In the 4-week telerehabilitation programme, participants received the 'Smart Reminder' wristwatch and were instructed to wear it on their affected arm for a minimum of 3 hours a day for five days a week. During the 3-hour wear period, the device would vibrate and emit an auditory beep to remind participants to perform their prescribed exercises. An occupational therapist trained the participants to operate the device and connect it to the telerehabilitation application on their smartphones. In addition, participants were orientated to interpret the performance indicator (i.e. visual feedback, see Figure 5.2b) during training. An operating manual for the device was also given to them. Participants were instructed to perform prescribed exercises, customised according to the severity of their upper limb paresis, for 15 minutes per session, three times a day, five times a week during the 4-week intervention period. The therapist remotely monitored the participant's daily exercise progress and sent reminders by text message to individuals who missed their exercise regime. Additionally, participants received a 30-minute in-person consultation session with the therapist weekly to review their progress and modify the prescribed exercises based on data provided by the wearable device.

Figure 5 -1: Study design

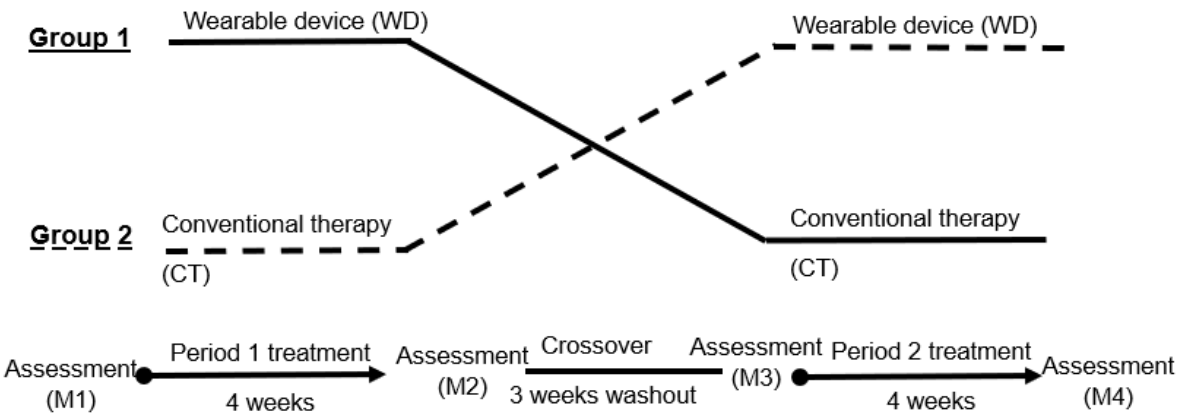


Figure 1: Study design. Two-period, controlled crossover design. Each period consisted of 45 mins per day of exercises, 5 times/per week, and 4 therapy consultations. 3-week washout was held between both periods. Assessments were done before period 1 treatment (M1), after period 1 treatment (M2), after crossover (M3) and after period 2 treatment (M4). Group 1= WD-CT; Group 2 =CT-WD.

Figure 5 -2 (a) The proposed wearable device, 'Smart Reminder'

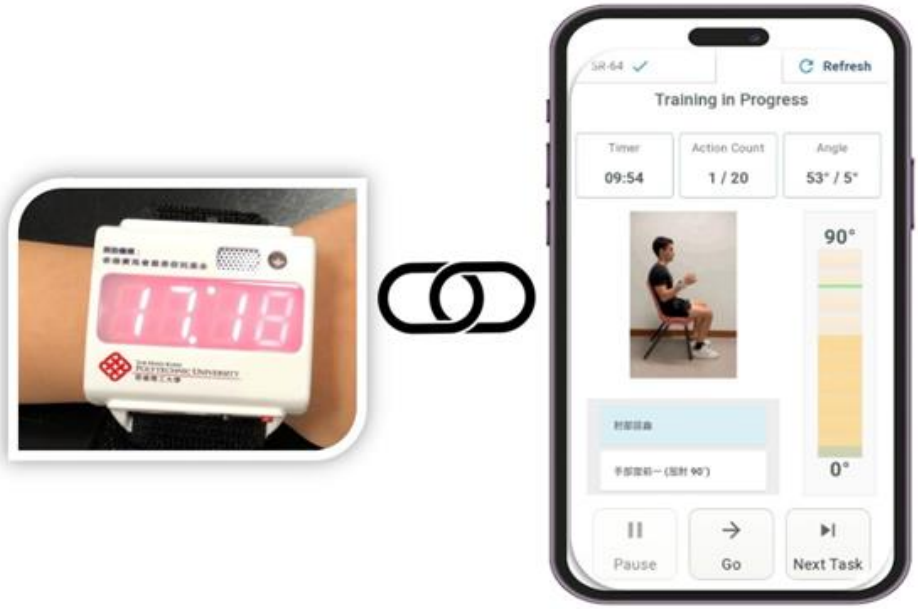


Figure 5 -2 (b) Telerehabilitation application

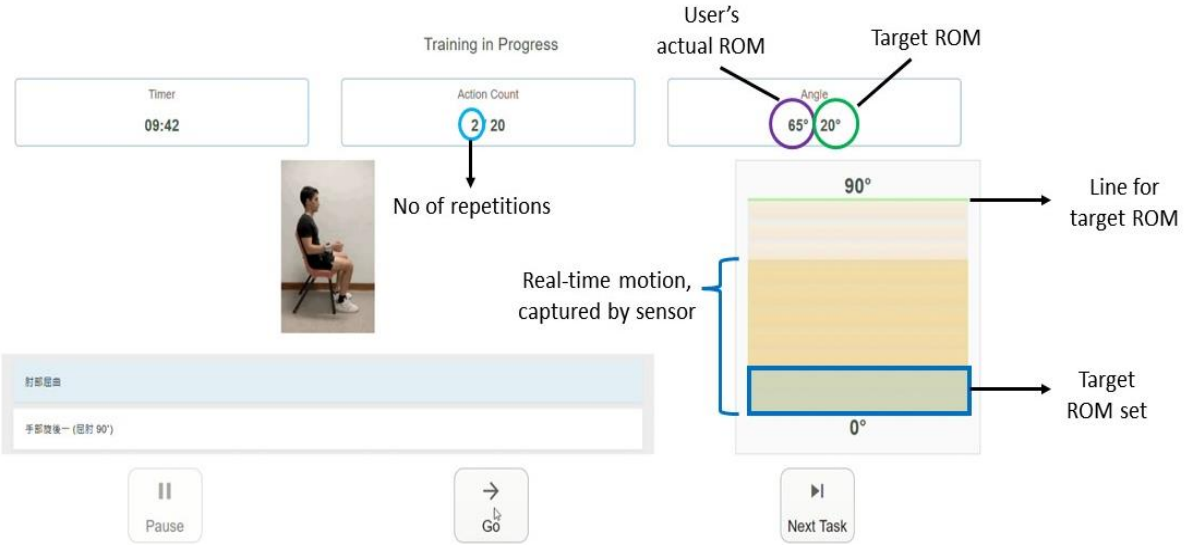
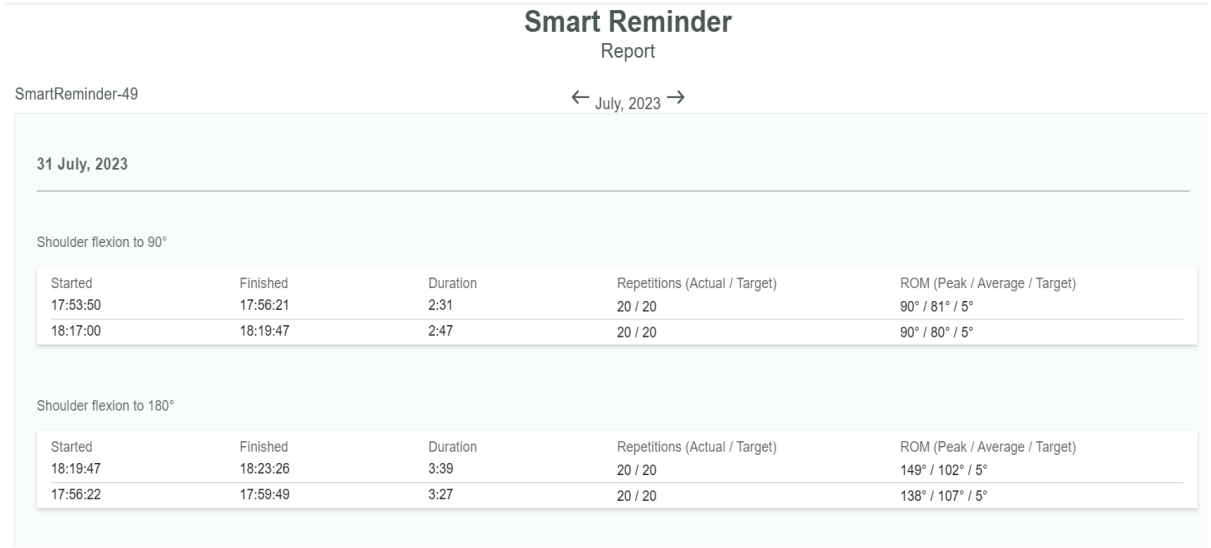


Figure 5 -2(c) Progress record



Smart Reminder

Report

SmartReminder-49

← July, 2023 →

31 July, 2023

Shoulder flexion to 90°

Started	Finished	Duration	Repetitions (Actual / Target)	ROM (Peak / Average / Target)
17:53:50	17:56:21	2:31	20 / 20	90° / 81° / 5°
18:17:00	18:19:47	2:47	20 / 20	90° / 80° / 5°

Shoulder flexion to 180°

Started	Finished	Duration	Repetitions (Actual / Target)	ROM (Peak / Average / Target)
18:19:47	18:23:26	3:39	20 / 20	149° / 102° / 5°
17:56:22	17:59:49	3:27	20 / 20	138° / 107° / 5°

During the 4-week conventional treatment, participants were taught a set of exercises similar to that used in telerehabilitation; the only difference was that the prescribed exercises were presented as a pictorial handout rather than an in-app video. During the intervention, they were instructed to perform the prescribed exercises for at least 15 minutes three times a day, five days a week. A 30-minute weekly in-person therapy consultation session was also provided, and participants were instructed to record their daily exercise compliance in an exercise log.

5.3.4 Data collection

Data were collected from pre-assessment on participants' demographics, including age, sex, the onset of stroke, side of hemiparesis, and upper limb disability according to the FTHUE-HK (Fong et al., 2004). The primary outcome measures were Fugl Meyer upper extremity assessment (FMA-UE) (Fugl-Meyer, Jääskö, Leyman, Olsson, & Steglind, 1975), Action Research Arm Test (ARAT) (Lyle, 1981), and active range of motion of the hemiplegic shoulder, elbow and forearm using a manual goniometer. The secondary outcome measures included the Motor Activity Log (MAL) (Taub et al., 2011) and the participants' adherence to therapy. Therapy adherence was expressed as a percentage of the average repetitions completed over the total number of exercise repetitions prescribed (Neibling, Jackson, Hayward, & Barker, 2021). Data on therapy adherence was retrieved from the web portal to which the wearable device transmitted data for the wearable device group and the participant's self-record exercise logsheet for the conventional therapy group. Outcome measures were evaluated at the following intervals: baseline (M1), post-treatment at 4 weeks (M2), after a 3-week washout period at crossover before beginning the second intervention (M3), and after the second intervention (M4). To ensure the reliability of the measured results, the same assessor evaluated their assigned patients during the pre-test, post-test, and follow-up evaluations (Fong et al.,

2011). All outcome measure assessors were adequately trained to conduct the assessments and were not the same person as the attending therapist.

5.3.5 Data Analysis

Descriptive statistics on demographics and clinical scores of participants were presented in mean and standard deviation (SD), absolute number, or percentage. Data were tested for normality using the Shapiro-Wilk test. Chi-square and Mann-Whitney tests were used to measure the differences in baseline data and demographic variables between Group 1(WD-CT) and Group 2 (CT-WD). Before analysing the effect of the treatment, a carryover effect was assessed using the method recommended by previous studies (Sczesny-Kaiser et al., 2019; Wellek & Blettner, 2012). The carryover effect was evaluated using the sum of measured values in the two intervention periods [after treatment after the first intervention (M2) and at the end of the study after the second intervention (M4)] in each patient and compared between two groups using an unpaired t-test (Wellek & Blettner, 2012). When the *p-value* was >0.05, it indicated no carryover effect, and the washout period was sufficient.

The treatment effects of telerehabilitation using 'Smart Reminder' device and conventional therapy were assessed by comparing all clinical outcomes before and after each treatment using the Wilcoxon signed rank test for the combined sample (i.e., 12 data points after the first intervention and 12 data points after the second intervention) (Belmonte et al., 2012; Dong & Fong, 2016). Analysis of covariance (ANCOVA) was used to determine the difference between the treatment effects of both interventions: telerehabilitation using 'Smart Reminder' and conventional therapy. The covariate used in ANCOVA was identified through the baseline comparison between Group 1(WD-CT) and Group 2 (CT-WD) if any baseline variable showed a significant difference. Once the participants were assigned to a group and

started treatment, their results were included for data analysis based on the intention-to-treat principle. In the event of dropouts, the "last observation carried forward" (LOCF) was used, provided the missing data were not over 15%. The significance level of all tests was set at $p<0.05$ for the two-tailed analysis. All statistical analyses were performed with SPSS version 29.0 (SPSS Inc, Chicago, IL, USA).

5.4 Results

Twelve stroke participants (8 men and 4 women) were recruited from community support groups. Three participants in Group 1 (WD-CT) dropped out after completing the first intervention for medical reasons unrelated to the study intervention. No participants reported adverse effects after the study interventions or dropped out for intervention-related reasons. Figure 5.3 illustrates the CONSORT flow diagram of the study. The baseline demographic characteristics of the study participants are provided in Table I. There was no difference in demographic profile between Groups 1 and 2, except for the time since the stroke onset. Therefore, the time since stroke onset was used as the covariate for ANCOVA measures to compare the treatment effects of both interventions. The mean age of the study participants was 55.83(11.82) years, and the mean time since the stroke was 85.08 (64.11) months. Regarding carryover effects, statistical analysis revealed no carryover effects for all outcome parameters (shoulder flexion AROM: p= *0.837*; shoulder abduction AROM: *p=0.915*; Elbow AROM: *p=0.577*; pronation AROM: *p= 0.130*, supination AROM: *p=0.539*; FMA-UE: *p=0.915*; ARAT: *p= 0.868*; MAL-AOU: *p= 0.802*; MAL-QOM: *p= 0.655*), implying that the 3-week washout period was sufficient.

Table II shows the effect of each treatment on the combined sample. Firstly, the AROM of the participants' hemiplegic shoulders improved significantly in terms of flexion (8.9± 12.7,

p=0.022) and abduction (12.2 ±14.3, *p=0.018*) after the 'Smart Reminder' training. No significant differences were found in other upper limb outcomes after the 'Smart Reminder' training. Regarding the conventional therapy, no significant improvements were found in any of the upper limb outcomes after the training. Comparing the treatment compliance rates, the mean compliance rates among participants during the 'Smart Reminder' training and the conventional therapy were 78.25 percent and 70.5 percent, respectively, with no statistically significant differences using ANCOVA analysis.

Table III compares the two treatment effects in the combined sample (i.e., 24). When comparing the effect of training with the 'Smart Reminder' device and conventional therapy, the results of the ANCOVA analysis showed a significant difference between the treatments regarding shoulder abduction AROM [*p=0.036*, d=0.98 (converted from η^2=0.193)], with a large effect size according to Cohen.43 Further analysis showed that the hemiplegic shoulder abduction AROM of the participants significantly improved after the telerehabilitation training using the 'Smart Reminder' compared to after the conventional therapy (mean difference=10.90, 95% CI 0.79-21.04). No significant differences were found in other outcome measures when comparing the treatments.

Figure 5-3:The CONSORT diagram

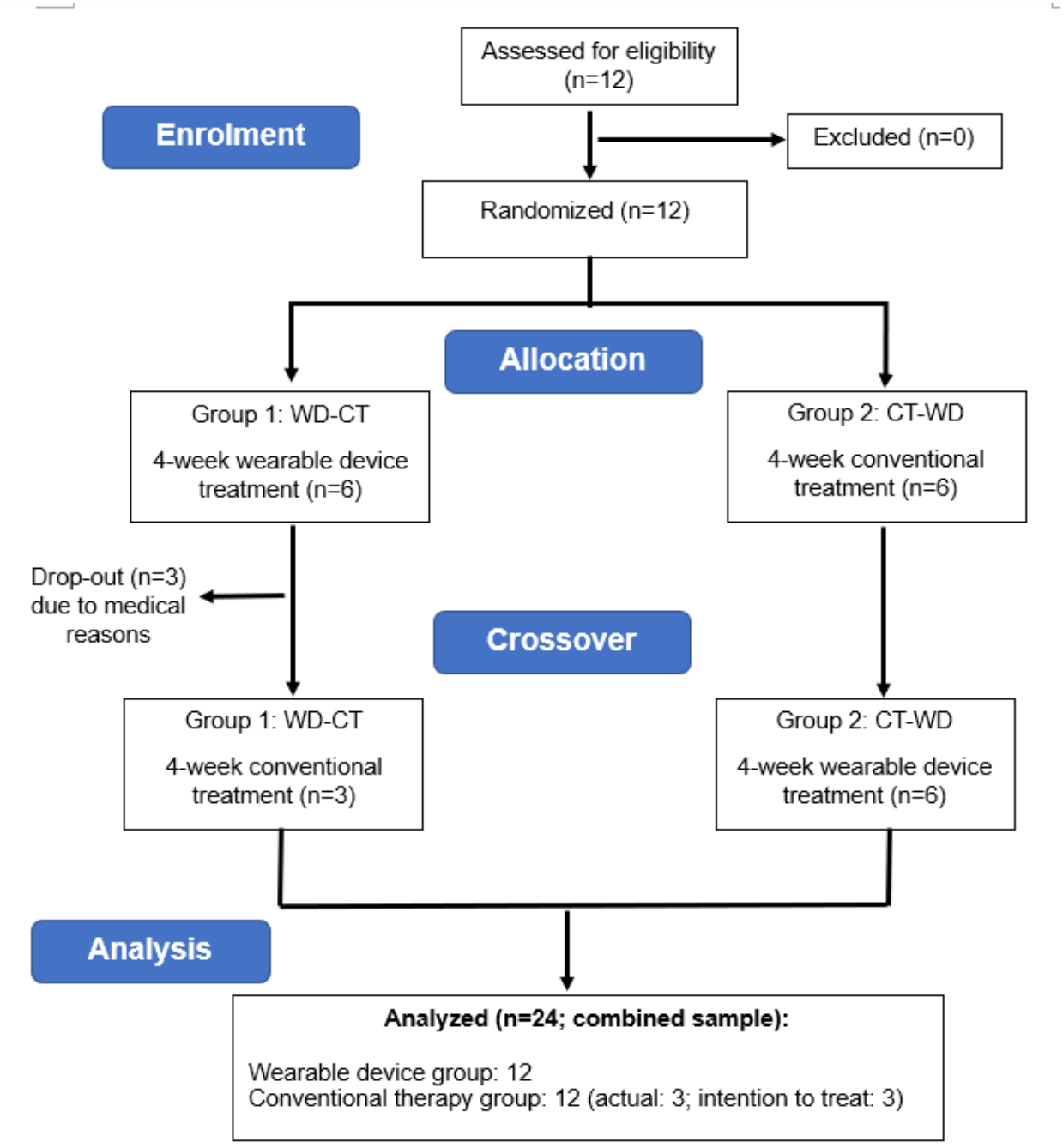


Table 5- 1: Baseline demographic and clinical characteristics

	Whole sample (n=12)	Wearable device* group (n=6)	Conventional treatment* group (n=6)	Demographics comparison between two groups (*p*-value)
Age (years)	55.83 (11.82)	51.00 (15.58)	60.67 (2.88)	0.59[b]
Gender				
Male	8 (66.7%)	5 (83.3%)	3 (50%)	0.22[a]
Female	4 (33.3%)	1 (16.7%)	3 (50%)	
Time since onset (months)	85.00 (64.23)	42.50 (36.82)	127.50 (58.18)	0.015[b]
Side of hemiparesis				
Right	8 (66.7%)	5 (83.3%)	3 (50%)	0.22[a]
Left	4 (33.3%)	1 (16.7%)	3 (50%)	
Upper limb severity (FTHUE-HK: score 1-7)	4.42 (1.68)	4.33 (0.62)	4.67 (0.67)	0.94[b]
Shoulder flexion ROM	115.58 (48.26)	112.00 (49.26)	119.17 (51.63)	0.94[b]
Shoulder abduction ROM	106.75 (48.43)	99.17 (37.26)	114.33 (60.29)	0.82[b]
Elbow ROM	110.75 (28.74)	112.00 (26.70)	109.50 (33.18)	0.82[b]
Pronation	55.83 (28.67)	63.00 (18.66)	48.67 (36.57)	0.70[b]
Supination	58.17 (34.13)	62.33 (30.83)	54.00 (39.63)	0.82[b]
FMA-UE	42.92 (14.72)	43.83 (12.08)	42.00 (18.18)	0.70[b]
ARAT	25.92 (21.84)	24.50 (21.46)	27.33 (24.19)	1.00[b]
MAL-QOM	1.43 (1.43)	1.22 (1.64)	1.64 (1.30)	0.49[b]
MAL-AOU	1.25 (1.23)	1.14 (1.50)	1.36 (1.03)	0.59[b]

[a]Chi-square, [b]Mann-Whitney U test; *Wearable device and Conventional treatment group: group allocation before crossover; FTHUE-HK: Functional Test for Hemiplegic Upper Extremity-Hong Kong version; ROM: range of motion; FMA: Fugl Meyer Upper limb Assessment; ARAT: Action Research Arm Test; MAL-QOM: Motor Activity Log-Quality of movement; MAL-AOU: Motor Activity Log- Amount of use

Table 5-2: Within group effect

Outcome changes after each treatment in the combined sample, Mean (SD) (n=24)						
	Wearable device treatment (n=12)			Conventional therapy treatment (n=12)		
Variables	Pre	Post	*P*-value[a]	Pre	Post	*P*-value[a]
Shoulder flexion AROM	114.83 (47.54)	123.75 (48.28)	0.022	124.58 (46.56)	124.50 (50.13)	0.953
Shoulder abduction AROM	108.17 (46.67)	120.33 (41.19)	0.018	113.92 (48.74)	115.17 (45.00)	0.513
Elbow AROM	112.58 (23.66)	117.00 (28.34)	0.125	114.67 (31.74)	112.83 (29.12)	0.514
Pronation	62.17 (24.21)	74.42 (10.62)	0.213	61.67 (29.27)	69.58 (22.52)	0.401
Supination	57.67 (35.15)	61.58 (32.82)	0.309	59.17 (34.63)	63.00 (30.45)	0.779
FMA	44.25 (12.95)	44.33 (14.03)	0.812	43.00 (14.34)	43.75 (13.88)	0.228
ARAT	26.00 (20.89)	28.00 (19.17)	0.159	26.58 (20.71)	27.67 (19.90)	0.071
MAL-QOM	1.45 (1.42)	1.45 (1.55)	0.919	1.36 (1.43)	1.40 (1.48)	0.400
MAL-AOU	1.33 (1.29)	1.39 (1.34)	0.677	1.31 (1.41)	1.46 (1.49)	0.293
Compliance rate (%)	-	78.25 (21.34)	-	-	70.58 (19.44)	-

P-value[a] for comparing pre- and post-treatment's mean rank after each treatment using Wilcoxon signed-rank test in the combined sample.
SD: standard deviation; AROM: active range of motion; FMA: Fugl Meyer upper limb assessment; ARAT: Action Research Arm Test; MAL-QOM: Motor Activity Log-Quality of movement; MAL-AOU: Motor Activity Log-Amount of use

Table 5-3: Between group comparison

Comparison of the effects of two treatments in the combined sample, Mean (SD) (n=24)				
Variables	After wearable device treatment (n=12) Improvement, mean (SD)	After conventional therapy treatment (n=12) Improvement, mean (SD)	*P-value*[b]	Effect size, η^2
Shoulder flexion AROM	8.92 (12.70)	-0.08 (9.44)	0.064	0.154
Shoulder abduction AROM	12.17 (14.26)	1.25 (8.61)	0.036	0.193
Elbow AROM	4.42 (9.48)	-1.83 (7.77)	0.070	0.148
Pronation	12.25 (28.41)	7.92 (22.44)	0.689	0.008
Supination	3.92 (14.03)	3.83 (18.75)	0.991	0.000
FMA	0.08 (3.85)	0.75 (2.63)	0.623	0.012
ARAT	2.00 (6.62)	1.08 (2.35)	0.659	0.009
MAL-QOM	-0.03 (0.33)	0.04 (0.43)	0.786	0.004
MAL-AOU	0.06 (0.38)	0.15 (0.54)	0.610	0.013

P-value[b:] comparing mean change between both groups using ANCOVA; SD: standard deviation; AROM: active range of motion; FMA: Fugl Meyer upper limb assessment; ARAT: Action Research Arm Test; MAL-QOM: Motor Activity Log-Quality of movement; MAL-AOU: Motor Activity Log-Amount of use; η^2: Partial eta squared

5.5. Discussion

This study investigated the effects of a novel wearable device, 'Smart Reminder', integrated with a smartphone-based application to provide home-based upper limb telerehabilitation to community-dwelling stroke survivors. The main finding of this study was that noticeable improvements in the motor performance of the hemiplegic upper limb were found after the telerehabilitation training using the 'Smart Reminder' device. This improvement was indicated by increased shoulder AROM (flexion and abduction) after the training. Furthermore, participants had a statistically significant improvement in shoulder abduction after the telerehabilitation training using the 'Smart Reminder' compared to after the conventional therapy. This study demonstrated the superiority of the proposed wearable device's telerehabilitation training over conventional therapy in the home setting. Two previous studies (Dong & Fong, 2016; Wei et al., 2018) that applied similar wearable device treatment to persons with hemiplegia found consistent findings. These studies (Dong & Fong, 2016; Wei et al., 2018) used a wearable device to provide sensory cues to encourage participants to perform customized exercises for their hemiplegic upper limbs. Both studies (Dong & Fong, 2016; Wei et al., 2018) reported a significant improvement in the motor performance of the hemiplegic upper limb after training with the wearable device. However, a marked difference in this study is that in addition to the sensory cueing function, the 'Smart Reminder' device integrates with a telerehabilitation application in the smartphone to provide visual feedback to participants, something which was absent in these studies (Dong & Fong, 2016; Wei et al., 2018) mentioned above.

The favourable motor gain after the telerehabilitation training using the 'Smart Reminder' in this study suggested that the multimodal feedback system provided by this wearable device was more effective in training the upper hemiplegic limb than the pictorial handouts used in conventional therapy. Previous studies (Moinuddin et al., 2021; Sigrist, Rauter,

Riener, & Wolf, 2013) have supported that multimodal feedback is more effective than single mode for motor relearning learning. One reason is that the human brain processes information better and faster if simultaneous feedback is presented from different modalities (Moinuddin et al., 2021). During telerehabilitation training using the 'Smart Reminder', participants received multimodal feedback (visual and auditory) concurrently on their performance. This multimodal feedback from the telerehabilitation increases the patient's knowledge of their performance, stimulating the learning process (Cirstea & Levin, 2007) and skill reacquisition (Molier, Van Asseldonk, Hermens, & Jannink, 2010). In addition to the real-time visual feedback on the participant's performance, the displayed targeted range of motion set by the therapist on the screen during the 'Smart Reminder' training also serves as a 'goal' for the participant, making the training goal-oriented. A review of the literature on motor learning and neurorehabilitation principles (Maier, Ballester, & Verschure, 2019) identified that knowledge of performance and goal-oriented training are essential components in neurorehabilitation. Therefore, multisensory concurrent feedback provided during telerehabilitation could benefit more than static pictorial handouts used in conventional training to promote motor gains in the hemiplegic upper limb.

One challenge of home-based rehabilitation was sustaining the participants' motivation. Cramer et al. (2019) highlighted that maintaining patients' motivation in unsupervised home therapies was challenging, with a high nonadherence rate of up to 70 percent (McLean, Burton, Bradley, & Littlewood, 2010). In the current study, participants showed better adherence to the 'Smart Reminder' training regime, with an average compliance rate of 78.25 percent, than conventional therapy, with a rate of 70.58 percent. This finding is consistent with Friedrich, Gittler, Halberstadt, Cermak, and Heiller (1998)’s study, which found that the motivational intervention exercise group had a better adherence rate (76.7 percent) than the conventional exercise group (69.4 percent). In addition to visual feedback, participants received auditory and

vibration signals from the wearable device as exercise reminders and remote monitoring by the therapist, both of which were absent in the control group . These factors might have improved the participants' motivation to comply with the upper limb training regime, possibly facilitating the observed improvement.

Despite the improvement in AROM for shoulder flexion and abduction, no significant improvements were found in other motor outcomes after telerehabilitation using the 'Smart Reminder'. This observation differed from another study (Wei et al., 2018) which found a significant improvement in ARAT in participants who had undergone sensory cueing treatment using wearable devices. There were two possible reasons for the lack of improvements seen in FMA-UE and ARAT in this study. First, in the study by Wei et al. (2018), participants were in the subacute stage of stroke, while most of our participants were in the chronic phase with a mean stroke onset of 85.08 ±64.11 months. Patients in the chronic stage were expected to maintain their residual functions, and further rehabilitation would result in a smaller motor gain for such patients (Murphy & Corbett, 2009), which might not reach statistical significance for a small sample size in this study. . Another possible explanation was the ceiling effects of the FMA-UE and ARAT measures for stroke patients with mild upper limb impairment (Carpinella, Cattaneo, & Ferrarin, 2014; H. H. Lee et al., 2021). A quarter of the participants in our study had mild upper limb impairment with high scores on the measures of FTHUE (i.e., 6-7), FMA-UE (i.e., >60) and ARAT (i.e.,>49) measures.

Another important finding in this study was that the conventional therapy group did not improve significantly in all the upper limb outcomes after treatment. This finding was consistent with a previous virtual reality (VR) study by Ballester et al. (2017). In that study, the authors found that compared with participants in their virtual reality group, participants in their control group, who underwent training in unassisted occupational therapy tasks at home, did not significantly improve in terms of upper limb outcomes. A meta-regression conducted in

2014 by Lohse, Lang, and Boyd (2014) highlighted a clear dose-response relationship with higher doses of therapy, leading to more significant improvement. Previous studies (Natta et al., 2021; Ward, Brander, & Kelly, 2019) that administered at least 90 hours of nontechnology-mediated treatment reported impressive motor gains, while other studies (Klamroth-Marganska et al., 2014; Winstein et al., 2016) that delivered 30hours or less reported marginal improvements in the affected arm. In particular, the control group, which underwent conventional therapy training in Ballester et al. (2017)'s study and our study, had only a cumulative training duration of 5 to 15 hours and 17 hours, respectively. In addition to the absence of augmented feedback, the relatively low therapy dose in our control group (i.e., < 90 hours) could result in a minimal improvement in motor function of the hemiplegic arm in our chronic stroke participants that was not statistically significant.

5.6 Limitations

This study has some limitations. First, this study used a small sample size and convenience sampling method, so its generalisability is limited. A study with a large sample size is recommended to assess the effects of the proposed wearable device. Second, this study adopted a crossover design; the effect of the treatment is compared with each participant since each participant serves as his or her control (Lim & In, 2021). In this manner, it removed the intersubject variability from the comparison between the groups and reduced the effect of covariates (Jones & Kenward, 2014). Nevertheless, one concern of this design is the carryover effect of the first treatment. This study adopted a 3-week washout period to rule out the carryover effect. This 3-week duration was longer than the 1-week washout period used in a previous study (Sczesny-Kaiser et al., 2019). Although statistical analysis showed no carryover effect was present, whether one could "wash out" the motor movements learnt within three

weeks remains uncertain. Finally, although stratification of the severity of upper limb disability was performed before randomization, the time of stroke onset was not considered. Therefore, the time of stroke onset was factored as a covariate during the analysis to mitigate this issue.

5.7 Conclusion

In the ever-changing rehabilitation landscape, the beneficial impacts of home-based wearable technologies provide valuable opportunities to move toward a more decentralised and self-directed paradigm. This study integrated wearable and smartphone technologies to offer stroke survivors an alternative way to perform upper limb training at home through intensive, self-directed, in-app exercises tailored to their varying upper limb needs. This study demonstrates the feasibility and effects of a 4-week home-based telerehabilitation using a novel wearable device to improve community-dwelling stroke survivors' hemiplegic upper limb function.

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Chapter 6: Effects of a Wearable-based intervention on the Hemiparetic Upper Limb in Persons with Stroke: A Randomized controlled Trial

This chapter examined the clinical effects of the enhanced version of 'Smart Reminder', a novel wearable device with telerehabilitation features to provide home-based upper limb training for persons with stroke. This chapter was submitted as a manuscript to the Neurorehabilitation and Neural Repair Journal as

Toh, F. M., Lam, W. W., Gonzalez, P. C., & Fong, K. N. (2024). 'Smart reminder': A Randomized Controlled Trial on the effects of a wearable-based intervention on the hemiplegic upper limb in persons with stroke (under revision)

The manuscript, included below, has been formatted according to APA 6th to align with the thesis format. References are provided at the end of the thesis.

6.1 Abstract

Introduction: Wearables have emerged as a transformative rehabilitation tool to provide self-directed training in the home. **Objective:** In this study, we examined the efficacy of a novel wearable device, 'Smart Reminder' (SR), to provide home-based telerehabilitation for hemiparetic upper limb (UL) training in persons with stroke. **Method:** Forty stroke survivors from community support groups were randomized (stratified by the period after stroke onset and impairment severity) to either the 'Smart Reminder' (SR) group or the sham device group. Participants received either 20 hours of telerehabilitation using the SR device or training with pictorial handouts and a sham device over 4 weeks. In addition, all participants wore a standard accelerometer for 3 hours each day, five times a week, outside the prescribed training. Participants were assessed by a masked assessor at baseline (Week 0), post-intervention (Week 4), and follow-up (Week 8). The outcome measures included Fugl Meyer Assessment for Upper Extremity (FMA-UE), Action Research Arm Test (ARAT), Motor Activity Log (MAL), muscle strength , active range of motion and amount of movement of the UL, and compliance rate of training. **Results:** The SR group improved substantially in their FMA-UE scores after treatment *(p=0.036)* compared to the sham group. Also, adherence to the training using the SR device was significantly higher, 97%, than the sham group, 82.3% *(p=0.038)*. **Conclusion:** A 4-week telerehabilitation programme using a 'Smart Reminder' device demonstrated potential efficacy in improving motor impairments (such as FMA-UE scores) of the hemiparetic upper limb. However, it did not significantly enhance the performance of the affected limb in daily activities.

Keywords: home-based intervention, wearable technology, telerehabilitation, stroke, upper limb

The trial was registered on ClinicalTrial.gov (URL: http://www.clinicaltrials.gov) with the identifier NCT05877183.

6.2 Introduction

Stroke is a leading cause of disabilities, significantly impacting the quality of life of stroke survivors and imposing substantial socioeconomic burden on families and society. Upper limb (UL) impairment is a major contributor to the loss of independence in stroke survivors (Faria-Fortini, Michaelsen, Cassiano, & Teixeira-Salmela, 2011) with its recovery rate generally poor(Brauer, Hayward, Carson, Cresswell, & Barker, 2013). A study by Kwakkel and Kollen (2013) indicated that 30 to 66 per cent of stroke survivors had little to no hand function. Current evidence suggests that a minimum dose of more than 20 hours over a month is needed optimal rehabilitation of the hemiparetic arm after a stroke (Hayward et al., 2021; Pollock et al., 2014), a requirement that is often unsustainable due to the constrained health services (Bernhardt, Chan, Nicola, & Collier, 2007; Clarke et al., 2018). Furthermore, clinic-based treatment lacks ecological validity of how the patients might transfer their learned skills in their homes and communities (Dobkin, 2017). More frequent and shorter intervals of exercise and motor skill training in the everyday environment may be more effective than individual clinic sessions (Bernhardt et al., 2016; Dobkin, 2017). Therefore, self-directed programs that allow patients to practise their skills at home after clinic treatment are increasingly favoured (Da-Silva, Moore, & Price, 2018; Da-Silva et al., 2019).

Wearable technologies, or wearables, have emerged as a transformative tool in rehabilitation, serving as as activity trackers, reminders, and connectors. These devices often include sensors that enable remote clinical monitoring outside of traditional healthcare settings (Cunha, Ferreira, & Sousa, 2023). The unique feature in wearable devices allows them to be a promising tool for self-directed training in the home environment (Maceira-Elvira, Popa, Schmid, & Hummel, 2019; Toh, Fong, Gonzalez, & Tang, 2023a). Wearables are electronic devices worn outside the body to track activity without restricting movement (Gao et al., 2016; Maceira-Elvira et al., 2019; Rodgers, Alon, Pai, & Conroy, 2019). Some wearable devices can

be connected to smart devices such as smartphones, tablets, and computers, enabling virtual reality (VR) training and telerehabilitation (Ballester et al., 2017; Toh, Gonzalez, & Fong, 2023b; Wittmann et al., 2016). Others can provide augmented feedback essential for motor relearning (Lee et al., 2021; Schmidt, Lee, Winstein, Wulf, & Zelaznik, 2018), promoting therecovery of hemiparetic ULs (Kim, Parnandi, Eva, & Schambra, 2022).Augmented feedback is particularly beneficial for some stroke survivors with impaired intrinsic feedback mechanism (i.e., proprioception and sensation) (Van Vliet & Wulf, 2006; Wang, Markopoulos, Yu, Chen, & Timmermans, 2017). It can be delivered in single or multiple modes through visual, auditory and haptic input (Jakus, Stojmenova, Tomažič, & Sodnik, 2017; Moinuddin, Goel, & Sethi, 2021). Some wearable devices can emit sound and vibration to encourage the use of the affected arm during daily activities in stroke survivors (Da-Silva et al., 2019; Wei, Fong, Chung, Cheung, & Chow, 2019) or integrate with VR systems to provide performance feedback to the user (Ballester et al., 2017; Sanders et al., 2020; Wittmann et al., 2016).

In home-based stroke rehabilitation, wearable technologies are applied through VR, robotic, somatosensory stimulation, and accelerometer-based feedback (Toh et al., 2023aStudies have demonstrated the potential of wearable devices as an UL rehabilitation tool in improving motor performance of the hemiparetic UL (Ballester et al., 2017; Chae, Kim, Lee, & Park, 2020; Choudhury et al., 2020; Da-Silva et al., 2019; Palmcrantz, Pennati, Bergling, & Borg, 2020; Seim, Wolf, & Starner, 2021; Wei et al., 2019). However the earlier studies referenced (Ballester et al., 2017; Chae et al., 2020; Choudhury et al., 2020; Palmcrantz et al., 2020; Seim et al., 2021; Wei et al., 2019) utilized a wide variety of interventions such as VR, accelerometer-based feedback and somatosensory stimulation. Previous reviews (Kim et al., 2022; Wang et al., 2017) highlighted that there was insufficient high-quality evidence concerning the use of wearable devices for home-based rehabilitation. Most research focused on the assessment capabilities of wearable sensors rather than treatment potential t (Kim et al.,

2022; Maceira-Elvira et al., 2019; Rodgers et al., 2019). Therefore, the effect of wearable-based intervention in rehabilitating the hemiparetic ULs at home remains unclear in the current literature (Kim et al., 2022; Parker, Powell, & Mawson, 2020; Rodgers et al., 2019) , necessitating the need for further research to establish the clinical impact in home based rehabilitation (Wang et al., 2017; Rodgers et al., 2019).

Our study introduces a wearable device called 'Smart Reminder' (SR) with two unique new features not found in previous wearable studies (Chae et al., 2020; Choudhury et al., 2020; Da-Silva et al., 2019; Da-Silva, van Wijck, et al., 2018; Palmcrantz et al., 2020; Wei et al., 2019; Whitford, Schearer, & Rowlett, 2020; Wittmann et al., 2016). Unlike earlier studies (Da-Silva et al., 2019; Da-Silva et al., 2018; Wei et al., 2019; Whitford et al., 2020) that only used an accelerometer, the SR wearable has an accelerometer and gyroscope sensors that track rotational movement. The gyroscope measures angular acceleration exclusively and is useful in measuring rotational projections such as range of motion (Aroganam, Manivannan, & Harrison, 2019; Passaro et al., 2017). In addition, the SR device connects to a smartphone telerehabilitation application (app) to offer interactive therapy and remote monitoring. The telerehabilitation app displays the prescribed exercises and the user's real-time movements (i.e. ROM of the UL), and completed repetitions.

The SR was developed based on our previous 'Remind to Move' (RTM) concept (Fong et al., 2011; W. X. J. Wei et al., 2019; X. Wei, 2018), which prompts patients to use their affected arm for ADLs. Similar to RTM, the SR device vibrates and beeps to remind users to perform prescribed exercises at scheduled times and regular intervals customized by the therapist. Furthermore, the telerehabilitation app of the SR includes exercise videos featuring simple functional tasks like wiping a table, pouring water, and picking up a cube, etc., along with standard range of motion (ROM) exercises for the upper limb. Notably, the SR intervention

uses a smartphone as a portable visual display, a feature generally absent in the existing wearable-based VR studies according to our recent scoping review (Toh et al., 2023a). Smartphones are advantageous due to their portability and high global ownership rates (Moral-Munoz et al., 2021). Our preliminary studies on SR wearable (Toh et al., 2023b; Toh, Lam, Gonzalez, & Fong, 2024) have shown promising results on the usability and feasibility of the SR wearable to provide a home-based UL telerehabilitation. However, a large-scale clinical trial is needed to confirm its efficacy.

In this study, we investigated the efficacy of an enhanced wearable device, SR, (Toh et al., 2023b; Toh et al., 2024) for home-based self-directed upper limb telerehabilitation in persons with stroke. The primary objective was to compare the effects of a 4-week SR telerehabilitation program to conventional training with a sham device on motor outcomes and arm use in the hemiparetic upper limb immediately after treatment. Additionally, we examined the long-term effects of SR telerehabilitation at a one-month follow-up. We hypothesized that the multimodal augmented feedback (active ingredient) from the SR telerehabilitation (delivery mode) would be more effective than conventional training with pictorial handouts using a sham device (delivery mode) in promoting motor recovery and arm use of the hemiparetic UL in persons with stroke.

6.3 Methods

6.3.1 Participants

Forty stroke participants were recruited from community self-help groups in Hong Kong using stratified convenience sampling from May to September 2023. The researchers screened the participants' eligibility according to the selection criteria: (1) age >18 years, (2) unilateral hemispherical involvement, (3) diagnosis of stroke with onset more than 3 months

(Lee et al., 2018), (4) Functional test for upper extremity-Hong Kong version (FTHUE-HK) (Fong et al., 2004) score between 3 and 6 (maximum of 7), (5) no complaint of excessive pain and swelling over the hemiplegic arm, (6) Modified Ashworth scale ≤ 2, (7) Mini-Mental State Examination (MMSE) ≥ 19 (Wei et al., 2019) and (8) able to follow verbal instructions and 2-steps command in using the wearable device and smartphone.

Participants were excluded if they were: (1) participating in another similar form of experimental study during the study period, (2) had botulinum toxin injection in the past 3 months, (3) had other significant UL impairment, i.e., fixed contractures, frozen shoulder, and pain, (4) diagnosed with conditions that would affect them using the device, i.e. visual impairment, active cardiac problems, and palliative treatment, and (5) not fully vaccinated against COVID-19. This study was approved by the Human Studies Committees of the Hong Kong Polytechnic University (HSEARS20230317001) and registered on ClinicalTrial.gov (URL: http://www.clinicaltrials.gov) with the identifier NCT05877183. Informed consent forms were signed by the participants before data collection. After completing the study, the participants were given a grocery voucher to compensate for their transportation expenses.

6.3.2 Study Design

This study was a single-blinded, randomized, controlled trial from May 2023 to December 2023. The CONSORT Checklist (Schulz, Altman, & Moher, 2010) guided this study. Using block randomization, participants were randomly assigned to two arms - Group 1 (SR device group) or Group 2 (sham device group) by a non-team member. The randomization was stratified according to the participant's baseline UL severity and stroke onset. A TIDieR checklist (Hoffmann et al., 2014) was used in this study to detail the intervention, instrumentation, procedures, and outcome measures.

Only assessors who conducted outcome measures on participants were blinded to treatment allocation. The assessor was a qualified occupational therapist trained in using the outcome measure, not the attending therapist. Masking in treatment allocation for attending therapists and participants was not feasible due to the nature of the intervention.

6.3.3 Sample size calculation

The sample size was calculated using the effect size of our previous feasibility study (Toh et al., 2024), in which the effect size of the primary outcome measure (shoulder abduction ROM) was η^2=0.193 using analysis of covariance (ANCOVA). Considering that there would be three repeated measurements and an estimated 25% attrition rate, a sample size of 40 participants for two groups is needed to achieve 90% in power and Type I error set at a 0.05 significance level calculated using G*power, Version 3.1.9.7 (Faul, Erdfelder, Lang, & Buchner, 2007). Therefore, a total sample of 40 participants was recruited in this study, with 20 per group.

6.3.4 Instrumentation

This study used two wearable devices- the SR device and a triaxial accelerometer. The SR (Figure 6.1) is a lightweight wristwatch-like device measuring 6.5 x 6.0 x 2.5 cm and weighing 70g, designed ergonomically with easily adjustable velcro straps. The SR had an in-built accelerometer, gyroscope sensors, and a rechargeable battery that could be used for up to 72 hours. The device vibrated and beeped to remind users to perform prescribed exercises at scheduled times and regular intervals, as customized by the therapist. Its Bluetooth function, connected to a telerehabilitation app on a mobile phone or tablet, allows participants to watch training videos, which include simple functional tasks and standardized upper limb ROM exercises .

During telerehabilitation, participants watched the prescribed exercise videos on their mobile phones in the app and performed the customized exercises accordingly. Concurrently, they received real-time feedback on their range of motion performance from the app on their phones. The built-in sensors in the SR device detected and recorded a participant's range of motion (ROM) and the number of completed repetitions. This information was displayed on the mobile phone's screen and uploaded to an encrypted web portal for the therapist to review remotely. The therapist could adjust the therapy parameters remotely based on the participants' ROM performance and compliance rate. The video exercises in the telerehabilitation app consisted of a range of motion exercises for the UL and functional and fine motor tasks. Some modifications on the current SR device were done after our usability study (Toh et al., 2023b). They included using a user-friendly velcro strap that supported single-handed use and the addition of functional and fine motor tasks in the app to increase the variety of exercises.

One of the study's aims was to objectively track the hemiplegic UL's use outside of the 'prescribed therapy' to encourage frequent use of the affected limb in the participants' daily routine. One limitation of the current SR device was that it could not track the UL movement

outside the telerehabilitation sessions when the device was off. Therefore, another wearable device (Figure 6.2), a triaxial digital inclinometer accelerometer, WT901C, by WitMotion Shenzhen Co., Ltd., with a size of 5.13 x 3.6 x 1.5 cm, was used together with the SR device in this study. This accelerometer served as the 'sham device' in the study's sham group. It resembled a wristband with a rechargeable battery that could last for 24 hours of continuous usage. The accelerometer tracked the participants' arm movements but did not emit any reminder or connect to a telerehabilitation application on the mobile device. During arm movements, the accelerometer recorded acceleration in three orthogonal directions (x, y, z) (van der Pas, Verbunt, Breukelaar, van Woerden, & Seelen, 2011). Additionally, the accelerometer had a sampling frequency range of 0.2 to 200 Hz and an acceleration measurement range of ± 16g. There was a micro-SD card in the accelerometer device for programming and recording kinematic data.

Figure 6-1: ‘Smart Reminder’ device

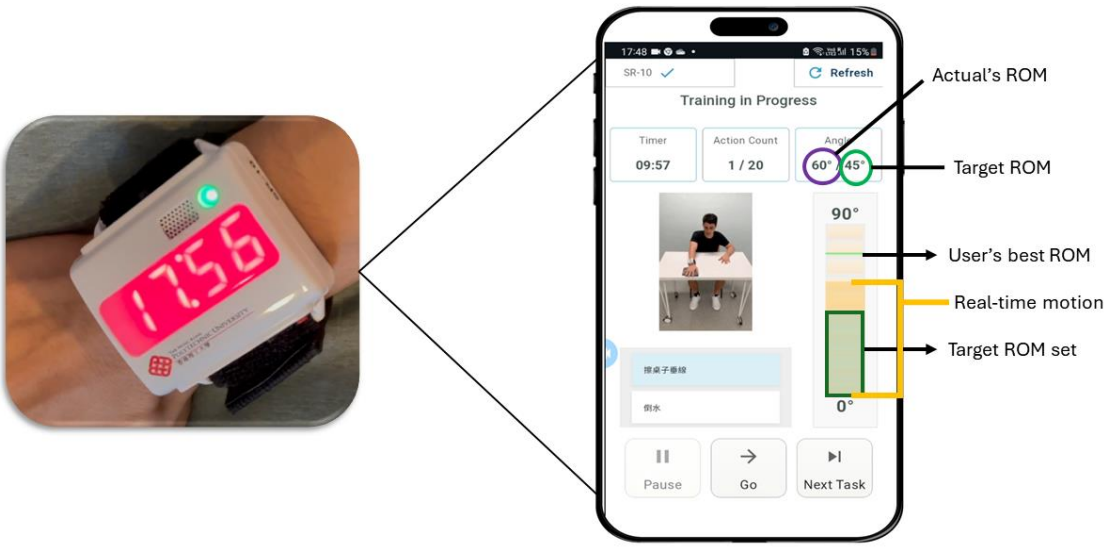


Figure 6-2: Sham device (standard accelerometer)

6.3.5 Intervention groups

Participants in the SR group wore the two wearable devices, the SR and the triaxial accelerometer (the same one as the sham device group), during the 4-week intervention period. They used the SR device for telerehabilitation training and wore the accelerometer outside of the telerehabilitation training to monitor their movement. Participants were taught how to operate both devices and connect the SR device to a telerehabilitation application downloaded on their mobile phones. The attending occupational therapists prescribed appropriate exercises from the app tailored to the severity of the participant's UL impairment. Also, the therapist set the frequency and duration of the exercise reminders emitted by the SR device after a discussion with the participants. The participants were instructed to engage in telerehabilitation training using the SR device for 1 hour per day, five times a week over 4 weeks. Outside the telerehabilitation session, the participants were asked to wear the triaxial accelerometer for 3 hours per day, five times a week and encouraged to use their affected arm in their functional activities over the intervention period. Previous studies (Seim et al., 2021; Wei et al., 2019) suggested that wearing the wearable device for three hours was intensive and appropriate; hence, in this study, we adopted the same wearing regime. The participants attended a 45-minute face-to-face consultation session with a therapist at a local university laboratory once a week, as recommended from the findings of our previous usability study (Toh et al., 2023b). This interim review allowed tailored adjustments to the prescribed exercises based on participants' progress and provided timely technical support. The therapist also reviewed the kinematic data from the SR device and accelerometer at least once before each weekly visit, ensuring continuous monitoring and timely adjustments to the therapy plan. During the visit, the therapist provided summary feedback on the participants' performance.

The participants in the sham device group received conventional training using similar types of UL exercises adapted to the severity of their UL impairment as that of the SR group

but with the prescribed exercises presented as a pictorial handout. During the 4-week intervention, they were instructed to exercise for one hour per day, five times a week, and to record their exercise in an activity log. Additionally, they were asked to wear the triaxial accelerometer (‘sham device’) during the prescribed one-hour training and another 3 hours per day, five times per week outside training. Outside the prescribed training, they were encouraged to use their affected arm in their functional activities while wearing the accelerometer to track their arm use. Like the SR group, they received a 45-minute consultation session once weekly with the therapist to modify the prescribed exercises according to their progress, except that no feedback was given on the amount of arm use.

6.3.6 Data collection and outcomes measures

Participants were assessed by assessor blinded to the group allocation at baseline before randomization (Week 0), post-intervention (Week 4), and follow-up (Week 8). The participants' demographics, such as age, sex, the period after stroke onset, side of hemiparesis, hand dominance and level of UL functioning based on the Functional Test of Hemiplegic Upper Extremity, Hong Kong version (Fong et al., 2004) were collected at baseline. The FTHUE-HK version (Fong et al., 2004) is based on Brunnstrom's developmental stages of stroke recovery. It categorises UL disability into seven functional levels, with the highest level being the least severe. The primary outcome measures in this study assess the hemiparetic upper limb (UL) across various levels according to the International Classification of Functioning, Disability, and Health (ICF) (Ustün, Chatterji, Bickenbach, Kostanjsek, & Schneider, 2003). Impairment measures include the Fugl-Meyer Assessment for Upper Extremity (FMA-UE), active range of motion (AROM) of shoulder, elbow, and forearm, and muscle strength of shoulder and elbow. Activity and participation are measured using the Action Research Arm Test (ARAT) and the

Motor Activity Log (MAL), respectively. Secondary outcomes include the amount of UL tracked by accelerometer in daily routines and the compliance rate of training.

The FMA-UE measures the synergistic pattern and ability to move arms (Fugl-Meyer, Jääskö, Leyman, Olsson, & Steglind, 1975) and is recognized as the gold standard in stroke research (Amano et al., 2020). The muscle strength of the hemiplegic elbow and shoulder of the participants was measured using a digital manual muscle tester (Nicholas manual muscle tester, Model 01160). The Nicholas manual muscle tester, a portable handheld dynamometer, measures force to 0.1kg with a range of 0.9 to 199.9kg (Sisto & Dyson-Hudson, 2007). It has an ergonomic design that supports the tester's hand and has a visible display to show the reading force output during a break test (Sisto & Dyson-Hudson, 2007). Additionally, a digital goniometer (Baseline 12-1027 Absolute Axis 360 Degree Digital Goniometer, Dedham, Massachusetts) was used to measure the active range of motion (ROM) of the hemiplegic shoulder (flexion/ abduction), elbow and forearm rotation (sum of supination and pronation).

Regarding the activity and participation measures, we assessed hemiplegic UL function using ARAT, the participants' subjective and objective arm use of their hemiplegic UL in daily routine using motor activity log (MAL) and the accelerometry arm movement, respectively. The subjective measure, the Motor Activity Log, MAL, a self-reported questionnaire, consists of two subscales to measure patients' perceived amount of arm use (MAL-AOU) and quality of arm use (MAL-QOM) (Uswatte, Taub, Morris, Light, & Thompson, 2006). Regarding the amount of movement, all participants wore the triaxial accelerometer on their affected arm for 3 hours per day, five times a week, to record the amount of arm movement. The raw acceleration data collected by the triaxial accelerometer was processed using five significant steps described in Figure 6.3 to calculate the amount of accelerometry arm movements, also termed ‘ movement counts’. These five steps are frequency filtering, rectification, thresholding, downsampling and activity accumulation. Firstly, a band-pass filter was applied with cut-off

frequencies set at 0.25Hz and 2.5Hz (van Hees, Pias, Taherian, Ekelund, & Brage, 2010) to eliminate the effect of gravity and invalid activities such as tremors and to attenuate background signal noise. Rectification of the raw accelerations in the three axes, x, y, and z directions over the 3-hour wearing period was performed to convert into a single signal using Pythagorean mathematics ($R= \sqrt{[x^2 + y^2 + z^2]}$) (van der Pas et al., 2011). Following the frequency filtering and rectification steps, upper and lower thresholds were applied to the rectified output. The upper threshold (set at 0.4g) removes outliners, such as instances of hitting, and the lower threshold (set at 0.09g) eliminates background noise in the time domain. Referencing previous literature (Brønd, Andersen, & Arvidsson, 2017; Brønd & Arvidsson, 2016), the output frequency was downsampled to 10Hz to ensure consistent movement counting. For the last step, activity accumulation, the acceleration data was processed into 'movement counts' using 1-second epoch time (Brønd et al., 2017). Lastly, the compliance rate of training for both groups was measured using the SR device's data log for the SR group and the activity log for the sham group.

6.3.7 Data analysis

Data analysis was conducted using SPSS software, version 26.0 (SPSS Inc, Chicago, IL, USA), based on an intention-to-treat principle once the participants started treatment. The method of 'last observation carried forward' (LOCF) was used if the drop-out rate did not exceed 10% (Wei et al., 2019). Baseline demographics and clinical scores of participants were presented in mean and standard deviation (SD), absolute number, or percentage. A comparison of baselines between the SR and sham device groups was performed using an unpaired t-test for normally distributed data, Mann Whitney U test for non-normally distributed data, and Chi-square for nominal data.

The treatment effect within each group (SR and sham groups) before/after treatment and at follow-up was assessed using single repeated measure of Multivariate Analysis of Variance (MANOVA) with Bonferroni post-hoc adjustment. For between-group differences, Multivariate Analysis of Variance (MANOVA) was used to analyze the change scores of the outcome measures to compare the treatment effect of the telerehabilitation provided by SR and conventional training supported with a sham device. In the event of significant differences, Bonferroni post-hoc test was performed.

The average movement counts of the participants' hemiplegic UL per hour over the 4-week intervention period were calculated and compared between groups to assess the amount of arm movement in the participants' daily routine. Lastly, the participants' mean compliance rate of training was calculated using the percentage of the total completed exercise sessions over the prescribed session. Using two-tail analysis, statistical significance was set at a *p-value* less than .05.

6.4 Results

Forty-eight stroke survivors from the community self-help groups in Hong Kong were screened from May 2023 to September 2023. Forty participants met the eligibility criteria and were recruited and randomized into the SR and sham device groups. The remaining eight stroke survivors did not fulfil the eligibility criteria because they did not meet the upper extremity functional levels (i.e. FTHUE level 3 to 6), indicating that they had either mild or very severe UL disability. Two participants from the sham device group dropped out before the completion of the intervention. One participant withdrew due to botulinum toxin injection, and another dropped out due to poor exercise tolerance as the participant could not tolerate the study's required exercise dose (i.e. 20 hours in total). One participant from the SR group missed the

follow-up assessment as the participant was overseas during the assessment period. The overall drop-out rate was 7.5%; therefore, all 40 participants were included in the data analysis based on intention-to-treat, and the LOCF method was used for the missing data. Figure 6.4 illustrates the CONSORT flow diagram of the study. The baseline demographic characteristics of the study participants were provided in Table 6.1, and there was no significant difference in the demographics between the SR and sham device groups.

6.4.1 Effect on upper limb motor recovery

Table 6.2 shows the treatment effects within each group immediately after treatment (at 4 weeks) and at follow-up (at 8 weeks). Result from a single repeated measure MANOVA indicated a significant multivariate effect of time on the upper limb outcomes for both the SR (Wilks' $\Lambda = 0.195$, $F_{22, 58} = 3.213$, $p=<0.001$) and sham device (Wilks' $\Lambda = 0.303$, $F_{22, 56} = 2.079$, $p=0.014$) groups. Follow up univariate ANOVAs revealed that the SR group experienced significant improvements in the impairment measures. After 4 weeks of treatment , there were notable gains in active range of motion (AROM) and muscle strength of the paretic elbow (elbow AROM: 7.52 ± 11.88°, $p = 0.032$; elbow flexion strength: 0.83 ± 1.32 kg, $p = 0.035$) and in FMA-UE scores (2.95 ± 3.55 points, $p = 0.004$). These improvements were sustained at the 8-week follow-up, with additional improvements in forearm rotation AROM (17.03 ± 28.89°, $p = 0.049$), muscle strength of the paretic elbow (0.84 ± 1.35 kg, $p = 0.035$), and FMA-UE scores (3.35 ± 3.42 points, $p < 0.001$).

Figure 6-3: Steps in processing raw acceleration to ‘movement counts’

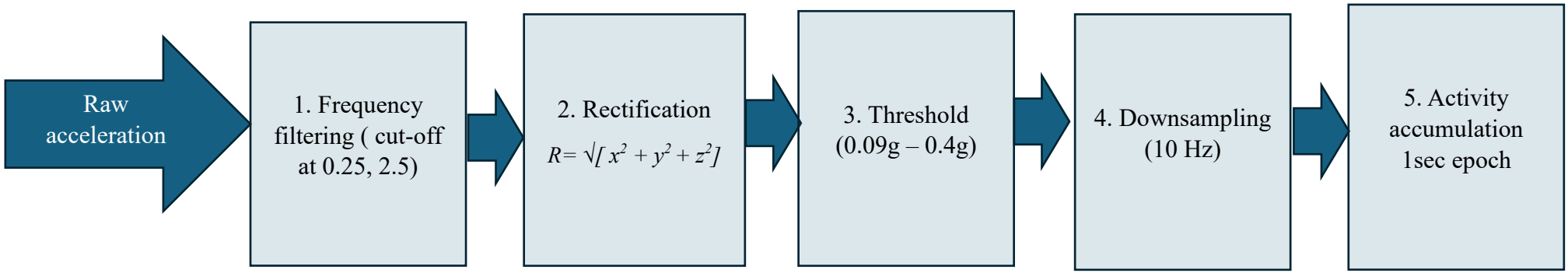


Figure 6-4: The CONSORT Diagram

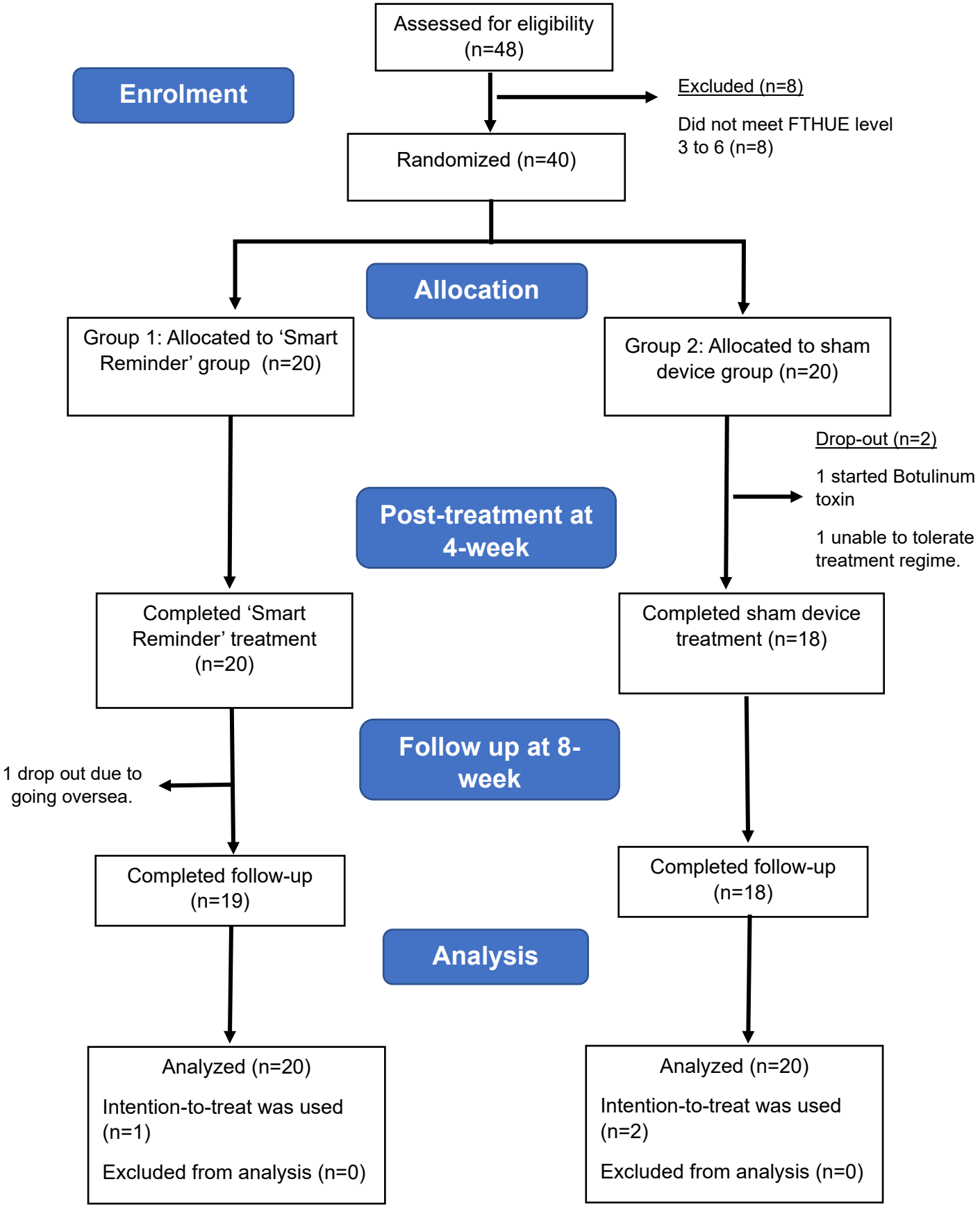


Table 6-1: Baseline demographic and clinical characteristics

	Wearable group (n=20)	Sham group (n=20)	Demographics comparison between two groups (*p*-value)
Age (years)	55.45 (9.98)	57.80 (9.22)	0.314[c]
Gender			
Male (%)	12 (60%)	13 (65%)	0.744[a]
Female (%)	8 (40%)	7 (35%)	
Time since onset (months)	84.05 (64.42)	70.55 (39.00)	0.799[c]
MMSE (score 0-30)	27.85 (1.60)	27.70 (2.49)	0.698[c]
Dominance of affected UL			
Dominant	9 (45%)	10 (50%)	0.752[a]
Non-dominant	11 (55%)	10 (50%)	
Upper limb severity (FTHUE-HK: score 1-7)	4.15 (1.14)	4.25 (1.16)	0.820[c]
Shoulder flexion AROM (°)	112.77 (34.99)	109.47 (32.69)	0.659[c]
Shoulder abduction AROM (°)	99.92 (31.38)	95.45 (30.39)	0.650[b]
Elbow AROM (°)	104.96 (34.63)	103.71 (27.60)	0.620[c]
Forearm rotation AROM (°)	120.57 (59.82)	126.68(41.67)	0.904[c]
Shoulder flexion MS (kg)	2.69 (2.25)	2.02 (2.16)	0.341[c]
Shoulder abduction MS (kg)	2.18 (2.42)	0.89 (1.60)	0.108[c]
Elbow flexion MS (kg)	2.02 (2.20)	2.15 (1.94)	0.620[c]
FMA-UE (score 0-66)	41.45 (13.99)	40.05 (11.54)	0.732[b]
ARAT (score 0-57)	20.65 (15.23)	19.30 (14.74)	0.777[b]
MAL-QOM (score 0-5)	0.84 (0.77)	0.53 (0.53)	0.231[c]
MAL-AOU (score 0-5)	0.80 (0.66)	0.66 (0.72)	0.495[c]

[a]Chi-square, [b]Independent t-test; [c]Mann Whitney test; MMSE: Mini-mental status examination; FTHUE-HK: Functional Test for Hemiplegic Upper Extremity-Hong Kong version; ROM: range of motion; MS: Muscle Strength; FMA-UE: Fugl Meyer Upper Extremity Assessment; ARAT: Action Research Arm Test; MAL-QOM: Motor Activity Log-Quality of movement; MAL-AOU: Motor Activity Log- Amount of use

Table 6-2: Comparison of upper limb outcomes within groups throughout 8 weeks, Mean (SD) (n=40)

Variables	'Smart Reminder' group (n=20)					Sham device group (n=20)				
	Pre	Post	8-week	p^a	p^b	Pre	Post	8-week	p^a	p^b
Shoulder flexion AROM (°)	112.77 (34.99)	117.81 (32.91)	115.86 (31.75)	0.137	0.927	109.47 (32.69)	110.69 (29.24)	110.64 (29.67)	1.000	1.000
Shoulder abduction AROM (°)	99.92 (31.38)	100.20 (36.04)	103.41 (31.40)	1.000	0.909	95.45 (30.39)	100.10 (33.86)	97.38 (31.82)	0.564	1.000
Elbow AROM (°)	104.96 (34.63)	112.48 (31.27)	108.42 (33.21)	0.032*	1.000	103.71 (27.60)	109.10 (25.80)	110.08 (25.76)	0.472	0.329
Forearm rotation AROM (°)	120.57 (59.82)	138.65 (40.63)	137.60 (46.84)	0.088	0.049*	126.68 (41.67)	135.63 (52.62)	136.51 (42.48)	0.750	0.255
Shoulder flexion MS (kg)	2.69 (2.25)	3.20 (2.25)	3.09 (2.33)	0.070	0.408	2.02 (2.16)	2.78 (2.49)	2.94 (2.43)	0.018*	0.020*
Shoulder abduction MS (kg)	2.18 (2.42)	2.66 (2.39)	2.77 (2.52)	0.701	0.401	0.89 (1.60)	1.82 (2.23)	2.25 (2.65)	0.018*	0.009**
Elbow flexion MS (kg)	2.02 (2.20)	2.85 (2.18)	2.87 (2.31)	0.035*	0.035*	2.15 (1.94)	2.74 (2.62)	3.04 (2.96)	0.123	0.061
FMA-UE (score 0-66)	41.45 (13.99)	44.40 (13.45)	44.80 (12.30)	0.004**	<0.001**	40.05 (11.54)	40.95 (12.17)	42.70 (11.74)	0.285	0.007**
ARAT (score 0-57)	20.65 (15.23)	20.05 (14.99)	20.25 (14.99)	0.990	1.000	19.30 (14.74)	17.90 (13.05)	17.90 (13.55)	0.208	0.196
MAL-QOM (score 0-5)	0.84 (0.77)	0.84 (0.89)	0.98 (1.01)	1.000	0.719	0.53 (0.53)	0.73 (0.63)	0.82 (0.83)	0.081	0.026*
MAL-AOU (score 0-5)	0.80 (0.66)	0.90 (0.81)	0.96 (0.90)	0.771	0.557	0.66 (0.72)	0. 73 (0.68)	0.82(0.87)	1.000	0.288

SD: Standard Deviation; AROM: Active Range of Motion; FMA-UE: Fugl-Meyer Upper Extremity Assessment; ARAT: Action Research Arm Test; MAL-QOM: Motor Activity Log-Quality of Movement; MAL-AOU: Motor Activity Log-Amount of Use; MS: Muscle Strength; p^a: p-value for comparing within-group after treatment after treatment using single repeated measure MANOVA with Bonferroni adjustment ; p^b: p-value for comparing within-group at 8-week follow-up using single repeated measure MANOVA with Bonferroni adjustment ; **p-value <0.01; *p-value <0.05

In the sham device group, participants showed a significant improvement in muscle strength of the paretic shoulder immediately after the 4-week treatment, with shoulder flexion increasing by 0.76 ± 1.09 kg (p=0.018) and shoulder abduction strength by 0.93 ± 1.35 kg (p=0.018). At the 8-week follow-up, these participants exhibited further improvements in their paretic upper limb outcomes. Muscle strength of the paretic shoulder continued to increase, with shoulder flexion strength reaching 0.91 ± 1.34 kg (p=0.020) and shoulder abduction strength rising to 1.36 ± 1.79 kg (p=0.009). Additionally, their Fugl-Meyer Assessment of the Upper Extremity (FMA-UE) scores improved by 2.65 ± 3.38 points (p=0.007), and their Motor Activity Log Quality of Movement (MAL-QOM) scores increased by 0.29 ± 0.44 points (p=0.026). No significant improvements in the Action Research Arm test (ARAT) were observed in either group.

Table 6.3 compares the treatment effects of both groups: the Smart Reminder and the sham device groups. The results of the MANOVA indicated a significant multivariate difference between the groups on the upper limb outcome measures at post-treatment (Wilks' $\Lambda = 0.380$, $F_{13, 26} = 3.258$, *p=0.005*). Further univariate ANOVA revealed a significant group difference in the FMA-UE scores, with the SR group showing a greater improvement than the sham device group ($F_{1, 38} = 4.71$, $p = 0.036$, $\eta^2 = 0.110$), indicating a medium effect size according to Cohen (Lindner, 1988). Post hoc analysis confirmed that participants in the SR group had significantly improved FMA-UE performance compared to those in the sham device group (mean difference = 2.05 points, 95% CI = 0.139 - 3.961). No significant differences were found in other outcome measures when comparing both groups after 4-week treatment and at 8-week follow-up.

Given the differences in FMA-UE score improvements between the two groups, further Mann -Whitney test analysis was conducted to assess the impact of the UL's severity on the treatment outcome, given the two groups' differences in the improvement in FMA-UE scores.

A cut-off score of 48 in the initial FMA-UE was used to differentiate participants with mild (≥ 48) and severe paresis (<48) (Hoonhorst et al., 2015). Figures 6.5a and 6.5b present the graphical displays for the changes in FMA-UE score s among the participants with severe and mild UL hemiparesis after the two treatments. For participants with severe UL paresis (FMA-UE score ranged from 17 to 46), the Mann-Whitney test showed a significant difference between both groups (U=37.5, Z= -2.61, *p=0.008*). The SR group significantly improved in their performance in FMA-UE compared to the sham group immediately after 4-week treatment with a mean difference of 3.38 points (see Figure 6.5a). At follow-up (8th week), both groups continued to improve in FMA-UE, and no significant difference between groups was observed. However, as shown in Figure 6.5b, no significant differences were found in the two groups for participants with mild UL paresis after treatment and at follow-up. At follow-up (8th week), the sham group continued to improve in their FMA-UE scores while the improvement of the SR group was maintained.

6.4.2 Therapy compliance and amount of paretic arm use

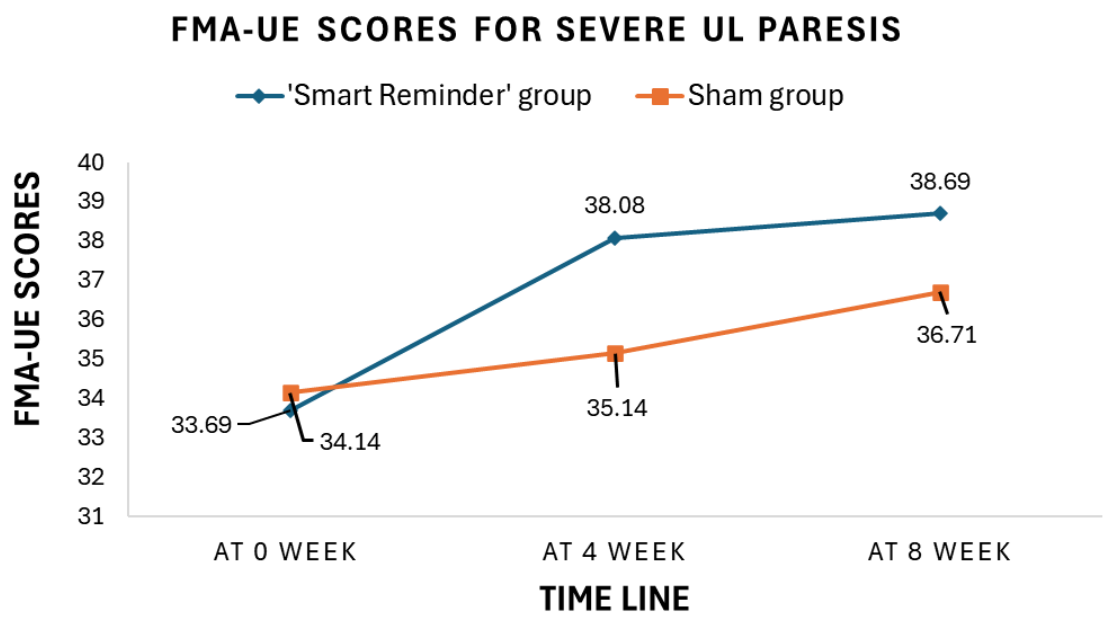
As can be seen from Table 6.3, the SR group had a significantly higher compliance rate to the therapy program than the sham group ($F_{1,38}$=4.62, p=0.038, η^2=0.108), with a medium effect size (Lindner, 1988). All the participants in both groups were given a standard accelerometer to wear for 3 hours outside the prescribed therapy exercises to collect their movement counts during their daily activities. Outside the prescribed therapy, the average movement counts per hour for the SR and sham groups showed no significant statistical difference ($F_{1,38}$=0.82, *p=0.371*, η2=0.021).

Table 6-3: Comparison of the treatment effects between groups throughout 8-week. Mean (SD) (n=40)

Variables	'Smart Reminder' group (n=20)		Sham device group (n=20)		Between-groups p^c	[c]Effect size η^2	Between-groups p^d	[d]Effect size η^2
	Δ post-treatment, Mean (SD)	Δ at 8-week, Mean (SD)	Δ post-treatment, Mean (SD)	Δ at 8-week, Mean (SD)				
Shoulder flexion AROM (°)	5.04 (10.52)	3.09 (13.63)	1.22 (9.63)	1.17 (9.35)	0.239	0.036	0.607	0.007
Shoulder abduction AROM (°)	0.28 (22.24)	3.49 (14.74)	4.65 (15.24)	1.93 (16.39)	0.473	0.014	0.753	0.003
Elbow AROM (°)	7.52 (11.88)	3.46 (16.37)	5.39 (16.37)	6.37 (16.97)	0.641	0.006	0.585	0.008
Forearm rotation AROM (°)	18.08 (34.28)	17.03 (28.89)	8.96 (33.75)	9.83 (24.19)	0.402	0.019	0.398	0.019
Shoulder flexion MS (kg)	0.51 (0.93)	0.40 (1.14)	0.76 (1.09)	0.91 (1.34)	0.454	0.015	0.197	0.043
Shoulder abduction MS (kg)	0.48 (1.74)	0.58 (1.66)	0.93 (1.35)	1.36 (1.79)	0.362	0.022	0.164	0.050
Elbow flexion MS (kg)	0.83 (1.32)	0.84 (1.35)	0.59 (1.21)	0.90 (1.59)	0.566	0.009	0.903	0.000
FMA-UE (score 0-66)	2.95 (3.55)	3.35 (3.42)	0.90 (2.29)	2.65 (3.38)	0.036*	0.110	0.519	0.011
ARAT (score 0-57)	-0.60 (2.68)	-0.40 (3.20)	-1.40 (3.25)	-1.40 (3.20)	0.401	0.019	0.330	0.025
MAL-QOM (score 0-5)	-0.00 (0.38)	0.14 (0.52)	0.20 (0.37)	0.29 (0.44)	0.098	0.070	0.346	0.023
MAL-AOU (score 0-5)	0.09 (0.36)	0.16 (0.51)	0.07 (0.38)	0.16 (0.41)	0.836	0.001	0.976	0.000
Compliance rate (%)	97.00 (6.37)	-	82.25 (30.02)	-	0.038*	0.108	-	-
Movement counts (per hour)	20224.38 (11767.08)		16910.25 (11367.00)		0.371	0.021	-	-

Δ: Change Score; SD: Standard Deviation; AROM: Active Range of Motion; FMA-UE: Fugl-Meyer Upper Extremity Assessment; ARAT: Action Research Arm Test; MAL-QOM: Motor Activity Log-Quality of Movement; MAL-AOU: Motor Activity Log-Amount of Use; MS: Muscle Strength; p^c: p-value for comparing between-group after treatment at 4 week using MANOVA with Bonferroni adjustment; p^d: p-value for comparing between-group at 8-week follow-up using MANOVA with Bonferroni adjustment ; Effect size, η^2: Partial Eta Squared; **p-value <0.01; *p-value <0.05

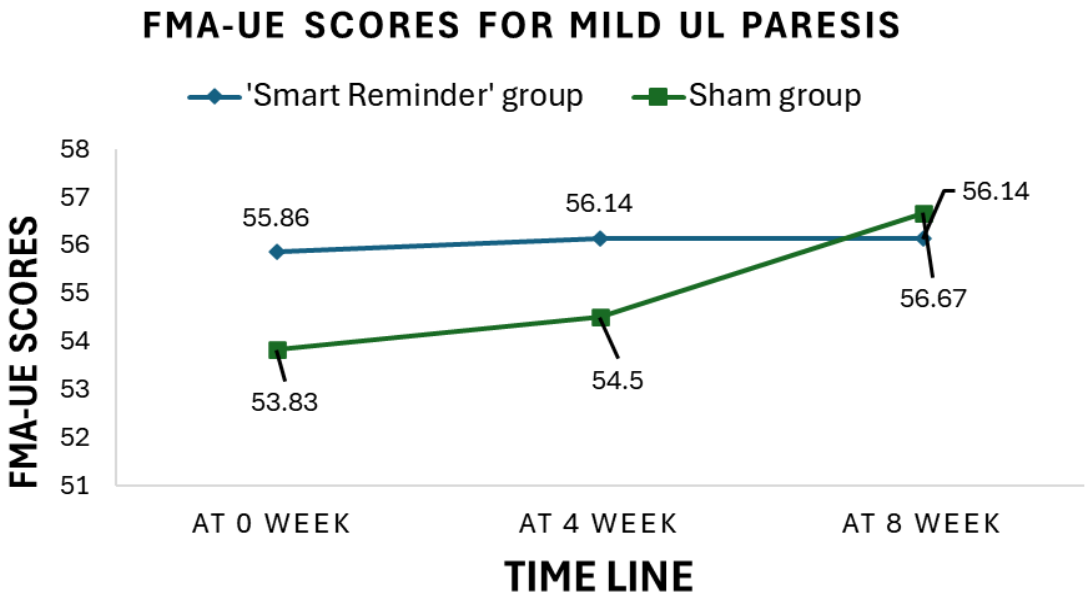
Figure 6-5 (a):FMA-UE scores for participants with severe UL hemiparesis at baseline, post-treatment, and follow-up (n=27; 'Smart Reminder' device group: n=13; sham device group: n=14) (FMA <48); **p-value <0.01.



	Δ post-treatment at 4 Week, Mean (SD)	Δ at follow up at 8 Week, Mean (SD)	Between-groups p^e	Between-groups p^f
'Smart reminder' group	4.38 (3.36)	5.00 (2.89)	0.008**	0.054
Sham Group	1.0 (2.29)	2.57 (3.69)		

Legend: p^e= p-value for change score in post treatment; p^f= p-value for change score at follow up

Figure 6-6 (b):FMA-UE scores for participants with mild UL hemiparesis at baseline, post-treatment, and follow-up (n=7; 'Smart Reminder' device group: n=; sham device group: n=6) (FMA ≥ 48)



	Δ post-treatment at 4 Week, Mean (SD)	Δ at follow up at 8 Week, Mean (SD)	Between-groups p^e	Between-groups p^f
'Smart reminder' group	0.29 (2.14)	0.29 (1.89)	0.836	0.138
Sham Group	0.67 (2.50)	2.83 (2.79)		

Legend: p^e= *p-value* for change score in post treatment; p^f= *p-value* for change score at follow up

6.5 Discussion

In this study, we investigated the effects of a wearable device, SR, integrated with telerehabilitation to provide home-based UL rehabilitation to stroke survivors in the community. Results showed that the SR group improved substantially in their FMA-UE scores after treatment compared to the sham group. Additionally, adherence to the SR telerehabilitation was significantly higher than that of the sham group. However, no significant differences were observed between the groups in other impairment outcomes or measures at the activity and participation levels of the ICF model, including the Action Research Arm Test (ARAT) and the Motor Activity Log (MAL).The study's findings demonstrated that the intervention provided by SR seemed more effective in improving the motor outcomes of the hemiplegic UL in the stroke participants than the conventional training using a sham device. The favourable motor gain and therapy adherence in the SR group suggested that the multimodal augmented feedback from the SR device had an added therapeutic value for UL recovery after stroke in the form of home-based rehabilitation. This observation was consistent with our previous feasibility study (Toh et al., 2024) on the SR device; in this feasibility study (Toh et al., 2024), apart from having a higher adherence rate, the active range of motion (ROM) of the participants' hemiparetic shoulders improved more significantly than conventional therapy after 4 weeks of telerehabilitation using SR device. Furthermore, the positive effect of the SR treatment was consistent with the results of previous studies (Ballester et al., 2017; Pawel Kiper et al., 2018; Lohse, Hilderman, Cheung, Tatla, & Van der Loos, 2014; Warland et al., 2019).

Several studies (Paweł Kiper, Agostini, Luque-Moreno, Tonin, & Turolla, 2014; Kiper et al., 2018; Lee et al., 2018; Subramanian, Lourenço, Chilingaryan, Sveistrup, & Levin, 2013) echoed the effectiveness of using enhanced feedback such as knowledge of results (KR) and performance (KP) in VR training for UL rehabilitation after stroke. Similarly, the participants received multimodal augmented feedback (visual and auditory) concurrently on the ROM

performance during the telerehabilitation using the SR device. Several pieces of evidence (Ballester et al., 2017; Cirstea & Levin, 2007; Jang et al., 2005; Tunik, Saleh, & Adamovich, 2013) suggest that augmented feedback, such as KR and KP, can modulate sensorimotor cortical activity by promoting learning in selected brain networks. Persons with stroke might benefit most from augmented feedback as their ability to generate intrinsic feedback to guide their performance was compromised due to neurological sensory impairments (Sabari, 2001). Hence, the multimodal augmented feedback provided during the SR treatment seemed more beneficial for the stroke participants in motor learning than static pictorial exercise handouts used by the sham device group. Moreover, the interactive visual environment provided by the telerehabilitation training using SR and the remote monitoring by the therapist motivated the participants to engage in the therapy regime, accounting for the high compliance rate.

The mean difference in the FMA-UE change score between the SR and sham group was 2.05. Although statistically significant, the difference is considered modest and falls below the recommended MCID for the FMA-UE - a lower minimal clinical important difference (MCID) for the FMA-UE for patients with chronic severe hemiparesis, specifically at 3.5points (Braden et al., 2023), compared to 4.25 to 7.25 points for participants with mild to moderate paresis (Page et al., 2012) and 12.4 points for participants with moderate to severe paresis in the early stroke phase (Hiragami, Inoue, & Harada, 2019). Notably, in the subgroup analysis of this study, participants with chronic severe hemiparesis (FMA-UE score of less than 48) in the SR group showed an average improvement of 4 points in their FMA-UE score immediately after treatment (Figure 6-5), meeting the proposed MCID for patients with chronic severe hemiparesis. This indicates that participants with more chronic severe hemiparesis appeared to benefit more from the multimodal augmented feedback provided by the SR device during UL training in this study.

This observation was supported by several studies (Cirstea, Ptito, & Levin, 2006; Cirstea & Levin, 2007; Jang et al., 2005; Subramanian, Massie, Malcolm, & Levin, 2010) highlighting strong evidence to support the effectiveness of augmented feedback for motor training of the severely impaired UL. In another study, Fong and colleagues (2011) also found that the UL function of their participants with more severe hemiparesis significantly improved after 2 weeks of sensory cueing treatment using a wearable device. One possible explanation is that participants with more severe hemiparesis had lower motor skill levels and more impaired sensory functions, making augmented feedback, i.e. ROM performance in this study, more useful. The stroke participants with more severe sensory impairments, such as proprioception, might rely more on extrinsic feedback to know what was needed to improve performance (Van Vliet & Wulf, 2006).

Furthermore, previous reviews (Lee et al., 2021; Wang et al., 2017) also highlighted that concurrent feedback suits individuals with low skill proficiency. During telerehabilitation provided by the SR device, participants received concurrent visual and auditory feedback that raised their awareness of the performance, enhancing their motor learning process. Participants with mild paresis, on the other hand, might have intact intrinsic feedback systems and were less reliant on the ROM feedback. Moreover, the ceiling effects of the FMA-UE in assessing persons with mild UL impairment (i.e. FMA-UE score $\geq$ 48) (Lee et al., 2021) might have contributed to the absence of treatment differences observed in both study groups.

Another interesting finding was that, despite the motor gains in the SR group as reflected in their FMA-UE scores, there was no significant improvement observed in the participants' ARAT and MAL scores. This observation suggests that the improvement in impairments was not substantial enough to create a change in the functional performance of the paretic UL or alter the participants' perception of using the affected upper limb in their daily

routine. One explanation is that most of the study participants had chronic severe hemiparesis, which previous studies have shown that these participants tend to correlate with low MAL scores and a reliance on the non-paretic upper limb for daily activities ((Bailey, Klaesner, & Lang, 2015; Stewart & Cramer, 2013; Tashiro et al., 2021). Furthermore, this study used the MAL-30, which has excellent internal consistency for individuals with mild to moderate paresis but is less sensitive for those with severe paresis ((Silva Esm, Pereira Nd, Gianlorenço Acl, & Camargo Pr, 2019).

Lastly, the study's results indicated that participants who received conventional therapy and sham devices also improved in their hemiplegic UL function but to a lesser extent. This observation differed from the author's previous feasibility study (Toh et al., 2024), where no improvement was found in the UL outcomes in the conventional therapy group. One possible reason was that the sham device group in this study received a sham device, which was an accelerometer, to track their daily UL movement. Despite the sham device not offering external feedback or connecting to a telerehabilitation app, its presence heightened participants' attention and awareness of their hemiparetic arm, thereby creating a 'treatment' effect on them. The knowledge that their UL movements were being monitored by their therapist could have motivated participants to exercise and use the affected arm in their daily activities Sandra and colleagues (2023) found that the placebo effect increases when devices are perceived as personalized which enhances treatment effectiveness. This is confirmed by the observation in this study that the SR and sham device groups did not differ significantly in their average hourly movement counts of the affected ULs during daily activities.

6.6. Limitations

This study has some limitations. Based on the recommendation by previous studies (Wei et al., 2019 ; Seim et al., 2021), participants were instructed to wear the accelerometer for 3 hours to capture their paretic UL movements in their daily routines. However, a 3-hour duration may be insufficient to accurately capture the actual real-life usage patterns for the paretic upper limb, potentially creating an upward biased as participants might intentionally increase their movement during the wearing period. Previous studies (Da-Silva et al., 2019; Lang et al., 2021) had adopted longer wearing durations of 12 hours or more to better capture the daily activity of the paretic upper limb.

In addition, the SR device could not track the amount of hemiplegic arms used by the stroke participants in their daily routine outside of therapy. A wearable device with dual functions, such as supporting the ‘ prescribed therapy’ and tracking the hemiplegic arm’s use in the stroke survivors outside of therapy, would be ideal to encourage intensive use of the affected UL in their daily routine to sustain the therapeutic gains (Toh et al., 2023a). Lastly, this study did not assess the arm use of the non-hemiparetic upper limb in the participants. Recent research (Hmaied Assadi, Barel, Dudkiewicz, Gross-Nevo, & Rand, 2022; Maenza, Good, Winstein, Wagstaff, & Sainburg, 2020) has indicated that participants with severe hemiparesis often exhibit significant motor deficits in their less-affected arm, which they heavily rely on for daily activities. Future studies may evaluate both the less affected and the hemiparetic arms using wearable technology, particularly in persons with severe hemiparesis.

6.7 Conclusion

This study integrated the technology of wearables and smartphones to provide alternative ways for stroke survivors to rehabilitate their hemiplegic ULs at home. The findings demonstrated that the telerehabilitation provided by the SR device was more efficacious than conventional training using a sham device in improving the FMA-UE scores of the hemiparetic UL in persons with stroke. However, it did not significantly increase the participants' perception in using their hemiparetic UL. Furthermore, adherence to telerehabilitation provided by the SR was excellent among stroke survivors. Further research is needed to explore the economic benefits of this novel device and its potential to offer valuable opportunities for self-directed rehabilitation, thereby easing the burden on conventional rehabilitation services.

6.8 References

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Chapter 7: Discussion and Conclusion

This chapter summarizes and discusses the main findings from the thesis research, discusses the conclusions that can be drawn from those findings, and ends with recommendations for future studies. Some of the material in this chapter was used in the author's submission of confirmation of registration as a full-time PhD candidate in the Department of Rehabilitation Sciences in September 2022.

7.1 Overview

This thesis is structured around a series of research studies that were conducted to inform and guide the application of wearable technology in home-based upper limb rehabilitation for persons with stroke. This final chapter outlines and synthesizes the key findings of the research studies series, which were undertaken in an effort to answer the overarching research questions and expand our knowledge in this field. The chapter discusses the conclusions that one can draw from those findings and their implications for clinical considerations of using wearable technology in stroke UL rehabilitation. The limitations of the studies and my recommendations for future research are also discussed.

In this thesis, I seek to answer four overarching research questions:

1. What essential elements are needed to successfully implement technology-based upper limb rehabilitation for persons with stroke in the home setting?
2. What is the current evidence for the application of wearable technologies in home-based UL rehabilitation for persons with stroke?
3. How usable and feasible is the study's proposed wearable device, "Smart Reminder," as a UL intervention for stroke rehabilitation?
4. After treatment and follow-up, is the enhanced version of the Smart Reminder wearable device more efficacious than conventional therapy that uses a sham device in promoting hemiplegic UL recovery in persons with stroke?

This PhD research comprised four stages that are conducted to answer these overarching research questions. **Stage One** consists of two review studies (discussed in Chapters 2 and 3, respectively) that formed the theoretical grounding of this thesis in my effort to address questions 1 and 2. The first review study (Study 1, in Chapter 2) is a systematic review and meta-analysis of the effects of home-based upper limb rehabilitation for stroke survivors. This

first review study examined the current evidence on the existing home-based UL interventions and identified essential elements required to successfully implement technology-based interventions in the home. A second review (Study 2, presented in Chapter 3) is a scoping review that examined the current evidence of wearable technologies in stroke rehabilitation in the home setting. A scoping review is usually used to clarify key concepts and characteristics and identify research gaps in new areas of research in which there is emerging and diverse evidence (Munn et al., 2018). The use of wearable technologies in home-based stroke rehabilitation is relatively new, so a scoping review has been chosen.

In **Stage Two** of my thesis research, I conducted a mixed methods usability study (Study 3, presented in Chapter 4) on the research's proposed wearable device, Smart Reminder, with a group of local stroke survivors. This study sought to identify three main areas of concern: (a) the functions and features of the wearable device, and which ones were valued by the stroke users versus which were disliked; (b) the participants' perceptions of the usability and acceptability of the wearable device; and (c) the features of the device that required further modification. The findings of the usability study then contributed to the enhancement of the existing SR device.

Following the usability study, a feasibility study (Chapter 5) has been carried out in **Stage Three** of the research to explore the feasibility and effects of the SR device as a home-based upper limb rehabilitation intervention to improve the hemiplegic UL motor function of persons with stroke. The feasibility study is a pilot randomized crossover trial that compared the effects of the telerehabilitation provided by the Smart Reminder device with the effects of conventional therapy in improving the hemiplegic upper limb function of the local stroke population. The findings of this feasibility study then contributed to the sample size calculation for a large randomized controlled trial, which is discussed in Chapter 6. Both the usability study (Chapter 4) and the feasibility study (Chapter 5) sought to answer question 3 concerning the

usability and feasibility of the proposed Smart Reminder device, as evaluated by the local stroke community, and to pave the way for the larger, randomized controlled trial described in Chapter 6.

The last study, Study 5, comprises the **final stage** of this PhD research and is presented in Chapter 6. Study 5 is a randomized controlled trial to examine the effectiveness of an enhanced version of the proposed SR wearable with telerehabilitation features in providing home-based self-directed UL training for persons with stroke. This study compared the improvements in the hemiplegic UL function of the local stroke community from the SR intervention with those from conventional therapy that used a sham device. Together, this knowledge can guide the application and selection of wearable technologies to provide UL rehabilitation for persons with stroke in the home context.

Chapter 7, which is the final chapter of this thesis, is organized into three sections: (a) a summary of key findings and the implications and conclusions that can be drawn from them, (b) a presentation of the implications for clinical applications, and (c) the limitations of the study and my recommendations for future research.

7.2. Summary of key findings and their implications

The research for this thesis produces several primary findings, as follows: (a) A consideration of multiple factors, such as motivation, social context, technical proficiency, physical space, and usability of the technological devices, is critical when implementing technology-based intervention in the home setting (Study 1). (b) Most of the research on wearable technologies in the home has focused on improving the hemiplegic upper limb, and few studies have focused on the lower limb and its physical function. Three critical features in the design of wearable devices are identified: an interactive, user-friendly interface, a fading

schedule in the feedback system, and a more portable display, such as a smartphone (Study 2). (c) The proposed SR device was usable, and its telerehabilitation intervention effectively promoted recovery of the hemiplegic UL (Study 3 & 4). (d) Augmented feedback from the SR-device intervention promoted hemiplegic UL recovery more effectively than the sham device treatment did, especially for individuals with more severe paresis (Study 5).

7.2.1 Considerations for implementing upper limb interventions using home-based technologies

Our first literature review (Study 1) demonstrated that after treatment and at follow-up, home-based UL interventions had improved the function of the hemiparetic ULs more effectively and had increased the satisfaction of stroke survivors in using their impaired arm in daily activities more than a clinic-based therapy had. Rehabilitating in the home brings an additional benefit to the treatment outcome—the fact that it provides context-dependent learning and uses daily objects that are relevant to the patients (Cunningham et al., 2016; Trombly & Wu, 1999). Patients who practice in a familiar environment are more likely to be able to transfer the acquired skills in real-life activities (Dobkin, 2017). Conversely, the clinic serves as a poor substitute environment in that it separates the individuals from the natural environment (Hillier & Inglis-Jassiem, 2010); furthermore, it may be inadequate and infeasible to transfer skills from a clinic environment to real-life situations (Tariah et al., 2010). Nonetheless, a key finding of this review (Study 1) is that "no-technology interventions," which used task-specific training, therapeutic exercises, and home-based constraint-induced movement therapy, are the main contributors to the positive effects of the home-based interventions, and all of those interventions requiredirect contact with the therapist, which currently is not sustainable because of the growing demand for rehabilitation services.

On the contrary, according to our literature review, the effects of home-based technology-assisted interventions have not been found to be superior to those from clinic-based therapy (Study 1, Chapter 2). Instead, one significant intention of using home-based technologies is to reduce direct contact with a therapist and improve the already-saturated health services (Akbari et al., 2021). This observation highlights the need to consider several factors when choosing a technology-assisted intervention for home-based UL rehabilitation: the person's motivation, social context, technical competence, the physical space, and the usability and therapeutic design of the technological devices (Adie et al., 2017; Chen et al., 2019). Insufficient consideration of these factors can affect the patient's motivation and therapy compliance, especially in the therapist's absence, thereby affecting the treatment results (Chen et al., 2019). The interface of our SR wearable and its training content in the user's smartphone application were customized for persons with stroke. Therefore, this PhD thesis included a usability study (Study 3) that adopted a mixed methods design to understand the users' perspectives and factors that would influence their intention to use the proposed wearable device.

7.2.2 Considerations for the design of wearable devices for clinical use

Our scoping review (Study 2) found that most of the research on wearable technologies applied in the home has focused on improving the hemiplegic upper limb, and few studies have been conducted to look at its effects on the lower limb and its physical function. Furthermore, this scoping review highlighted three design considerations for wearable devices intended to be implemented for clinical use. First, current virtual reality (VR) interventions using wearable sensors include computers, television monitors, or tablets as visual displays (Toh, Fong, et al., 2023). The use of smartphones has not been studied, although given their high global ownership, advanced processing ability, and integration of sensors and displays, recent smartphone technology advances clearly offer new options for VR training (Moral-Munoz et al., 2021). In

addition, a monitor or television display requires some setup and occupies physical space in the home, whereas smartphones are more portable than computers or television monitors are, so they allow users to conduct their training at their preferred locations (Toh, Gonzalez, & Fong, 2023).

Second, a fading schedule should be considered when designing the feedback system for wearable devices, and indeed, previous research suggests that a fading feedback schedule is essential for motor learning (Giraldo-Pedroza et al., 2020; R. Lee et al., 2021; Wang et al., 2017). As persons with stroke improve their motor skills in using their hemiplegic upper limb, they should rely less on the external feedback from the wearable device so that they can learn to use their intrinsic mechanism to maintain the skills they have learned.

Last, the most recent studies that used wearable devices as activity trackers did not include an interactive interface. Notably, however, Wang et al. (2017) highlighted that interactive therapy should be included in wearable-based interventions. The appropriate type of interactive therapy can be carried out via VR or telerehabilitation, in which the patients receive interactive stimulation through real-time visual and auditory feedback, thus enhancing their enjoyment during training sessions (H. S. Lee et al., 2019; Weiss et al., 2006).

On another front, the studies that used wearable VR interventions did not include a reminder system to encourage users to complete training. Stroke survivors need to be reminded and motivated to adhere to the training regime using their internal mechanisms. Wearable devices can have several functions, such as emitting reminders to users to move, supporting interactive therapy, and allowing therapists to monitor therapy remotely. In future studies, these multiple functions could be incorporated into a wearable device that can help a “prescribed” therapy (i.e., virtual reality) and be used as an activity tracker that emits reminders to encourage stroke survivors to use their impaired arms in their daily lives.

These three considerations were factored into the design of the proposed SR wearable device in this thesis, which has a reminder system to prompt the users to do their scheduled exercises. The system is integrated with a telerehabilitation application that is downloaded onto smartphones to allow stroke survivors to use it anywhere. In addition, the device's data are synced to an encrypted cloud server to enable the therapist to monitor the participants' progress remotely. As stroke participants gradually became accustomed to their exercise routines, the reminder schedule was adjusted to reduce their dependence on external prompts and aid them in learning to depend on their internal mechanisms.

7.2.3 Usability and effects of the Smart Reminder device as an upper limb intervention

Following the two review studies, three empirical studies (Studies 3, 4, and 5) were conducted to explore the usability and treatment effects of the SR device in providing upper limb training for people with stroke. The mixed-methods usability study (Study 3, Chapter 4) in this PhD thesis supported the usability of the SR device and demonstrated that this type of intervention was well-received as a home-based intervention for stroke survivors. Furthermore, this usability study identified four critical considerations to be taken into account when designing the wearable device and telerehabilitation program: wearability factors, the user interface, system performance, and exercise content.

Wearability factors, such as ease of wearing, unobtrusiveness, and being comfortable when worn, were emphasized in our usability study (Study 3, Chapter 4) and were also highlighted by previous studies (Cherry et al., 2017; Wang et al., 2017). Most persons with stroke have unilateral hemiparesis; the wearable device must support single-handed use, and the strap material must be comfortable enough to encourage long hours of wearing. Furthermore,

wearable devices such as the SR should be unobtrusive for outdoor use to avoid unnecessary public attention.

The second consideration was the device's user interface. The wearable device should be simple and easy to learn and have a user-friendly interface, hence reducing the cognitive load of persons with stroke and supporting their independent use of the device (Toh, Gonzalez, & Fong, 2023). Indeed, one key challenge faced by the participants in our usability study was one of technical issues, and previous studies also often highlighted technical problems when technology-based interventions were used (Chen et al., 2019; Cherry et al., 2017; Cranen et al., 2011; Kairy et al., 2013). Unlike the clinical environment in which professional technical support is offered, therapy conducted in the home requires patients and caregivers to solve the technical problems first-hand. A wearable device for home use should perform consistently in order to minimize the risk that users will lose confidence in the device's effectiveness and abandon it (Toh, Fong et al., 2023).

Third, the reliability and durability of the device's performance have been found to be important indicators of the abandonment of assistive technologies (Phillips & Zhao, 1993). Repeated functional testing and appropriate training in the use of the device are possible ways to minimize technical problems when implementing the device at home. Furthermore, timely technical support from caregivers and researchers is essential in order to ensure a positive user experience with home technologies (Chen et al., 2020).

The fourth consideration is the importance of having a wide variety of exercise content with graded difficulty levels. In our usability study, participants highlighted that access to a variety of exercise content with a graded difficulty level was essential to sustain their therapy engagement.

In this thesis, these four fundamental design considerations for a wearable device and its telerehabilitation program were applied in the final, largest study, which was a randomized controlled trial (Study 5, Chapter 6). For instance, the wearability of the SR device was improved by changing the strap to support single-handed use. Additional functional and fine motor tasks were added to increase the variety of the exercises. Moreover, participants received prompt technical advice and assistance when using the SR device, through their phones, via videos, and during onsite visits.

Prior to that extensive final RCT study, we conducted a pilot feasibility study (Study 4, discussed in Chapter 5) to explore the clinical effects of the telerehabilitation supported by SR on hemiplegic UL recovery. That feasibility study found that stroke participants had improved more significantly in their hemiplegic shoulder AROM after a 4-week home-based telerehabilitation using the SR device than they had after the conventional therapy. The beneficial motor gain that followed the telerehabilitation training using the SR indicated that the multimodal feedback system provided by this wearable device was more efficacious in training the hemiplegic UL than the pictorial handouts used in conventional therapy were. That observation was then further confirmed by the main study of this PhD research—the larger scale randomized controlled trial (Study 5, Chapter 6), which is reviewed in the next section.

7.2.4 Effect of augmented feedback from the 'Smart Reminder' on the motor recovery of the hemiplegic upper limb

Results from both the pilot feasibility study (Study 4) and the large RCT study (Study 5) of the SR device demonstrated that stroke participants showed noticeable improvements in their hemiplegic UL motor performance after four weeks of telerehabilitation using the SR device. Furthermore, this training mode was superior to conventional therapy conducted either with or

without a sham device. This observation supported the study's hypothesis that the multimodal augmented feedback from the SR brought an additional therapeutic effect in motor training of the hemiplegic UL, compared with the static pictorial handout used in the control group.

Several studies (e.g., Kiper et al., 2014; Kiper et al., 2018; S. H. Lee et al., 2018; Subramanian et al., 2013) have suggested that enhanced feedback through virtual reality (VR) training is beneficial in training the hemiplegic upper limb in persons with stroke. The enhanced feedback in VR training refers to information about knowledge of results (KR) and knowledge of performance (KP) (Kiper et al., 2018). Findings from several studies (Ballester et al., 2017; Cirstea & Levin, 2007; Jang et al., 2005; Tunik et al., 2013) have advocated that enhanced feedback, such as KR and KP, modulate the cortical activity of the sensorimotor cortex through facilitating learning in selected brain networks. In addition, other studies (Moinuddin et al., 2021; Sigrist et al., 2013) have indicated that multimodal feedback is more effective than unimodal feedback is for motor retraining. During the telerehabilitation training using the SR device in this thesis research, stroke participants received multimodal augmented feedback (visual and auditory) concurrently on their ROM performance and the results from the mobile phone's screen and the SR device. The multimodal feedback from the SR telerehabilitation improves the patient's understanding of their performance, stimulating the learning process (Cirstea & Levin, 2007) and skill retraining (Molier et al., 2010).

Another notable finding of the RCT study in this PhD research was that augmented feedback had a differential effect on the severity of upper limb paresis. Our RCT study found that participants with more severe hemiparesis (i.e., FMA-UE scores of less than 48) appeared to benefit most from the multimodal augmented feedback from the SR training. In contrast, the effects of the SR training were not significant in participants with mild paresis. This finding was consistent with the findings of a previous study by Fong et al. (2011), which indicated that participants with more severe hemiparesis improved significantly after two weeks of sensory

cueing using a wearable device. A plausible explanation for this differential response could be that stroke survivors with more severely impaired ULs have lower motor skill levels and more impaired sensory functions, in which augmented feedback is more beneficial. Stroke survivors with severe hemiparesis may need to rely on feedback from an external source, such as the SR device, to know what is required to improve performance (Van Vliet & Wulf, 2006).

Furthermore, concurrent feedback is found to be effective for individuals with low skill proficiency (R. Lee et al., 2021; Wang et al., 2017) because it supplements information on the performance of their affected internal feedback system. That dynamic is in contrast to participants with mild paresis, who may have intact internal feedback systems and, therefore, do not require external feedback from the device. Indeed, for those patients, the augmented feedback might conflict with their internal system (Molier et al., 2010).

Another key factor contributing to the positive outcomes observed in SR training is the application of motor learning principles. The SR intervention protocol is designed to promote intensive practice of the hemiparetic upper limb through telerehabilitation, while also counteracting learned non-use by tracking the hemiparetic arm usage with an accelerometer. V.S. Huang et al. (2011) demonstrated that motor learning is enhanced when newly acquired motor skills are practiced repeatedly, ensuring adequate sensorimotor mapping. The functional tasks include in the SR intervention, such as wiping a table or pouring water, are specifically chosen to provide this intensive, repetitive practice, allowing stroke participants to refine their motor skills and reinforce the sensorimotor mapping.

Additionally, several studies (Jaafar, Che Daud, Ahmad Roslan, & Mansor, 2021; Michielsen et al., 2011) have highlighted that motor skills acquired during an intervention can deteriorate rapidly if not consistently practiced, largely due to the phenomenon of 'forgetting' (Schmidt et al., 2018; Raghavan, 2015) in stroke survivors. To address this, the SR intervention

incorporates the use of an accelerometer to monitor hemiparetic arm usage and encourage the participants to use their hemiparetic arm as much as possible in their daily activities. This method aims to ensure that the therapeutic gains from telerehabilitation are sustained and that participants continue to practice these skills in their daily activities.

7.3 Clinical consideration of using wearable technologies in home-based stroke rehabilitation

Based on the main findings of this research, I have highlighted in Chapters 2 through 4 and have summarized in Figure 7.1 several considerations that should be followed in the design of a wearable technology-based intervention for home-based upper limb rehabilitation in persons with stroke. These considerations will significantly impact the successful implementation of this technology-based intervention in the home setting.

The wearable device should be easy to use, portable, and have high wearability. Furthermore, the device must perform consistently and include a wide range of exercises in its telerehabilitation programs. Maintaining the motivation of stroke survivors to engage in a therapy regime in an unsupervised environment, such as the home, can be challenging (Cramer et al., 2019). A high nonadherence rate in traditional home-based rehabilitation—70%—was highlighted in the review by McLean and colleagues (2010). Therefore, apart from a user-friendly, high-quality, and effective wearable device, additional considerations need to be made in planning the therapy program.

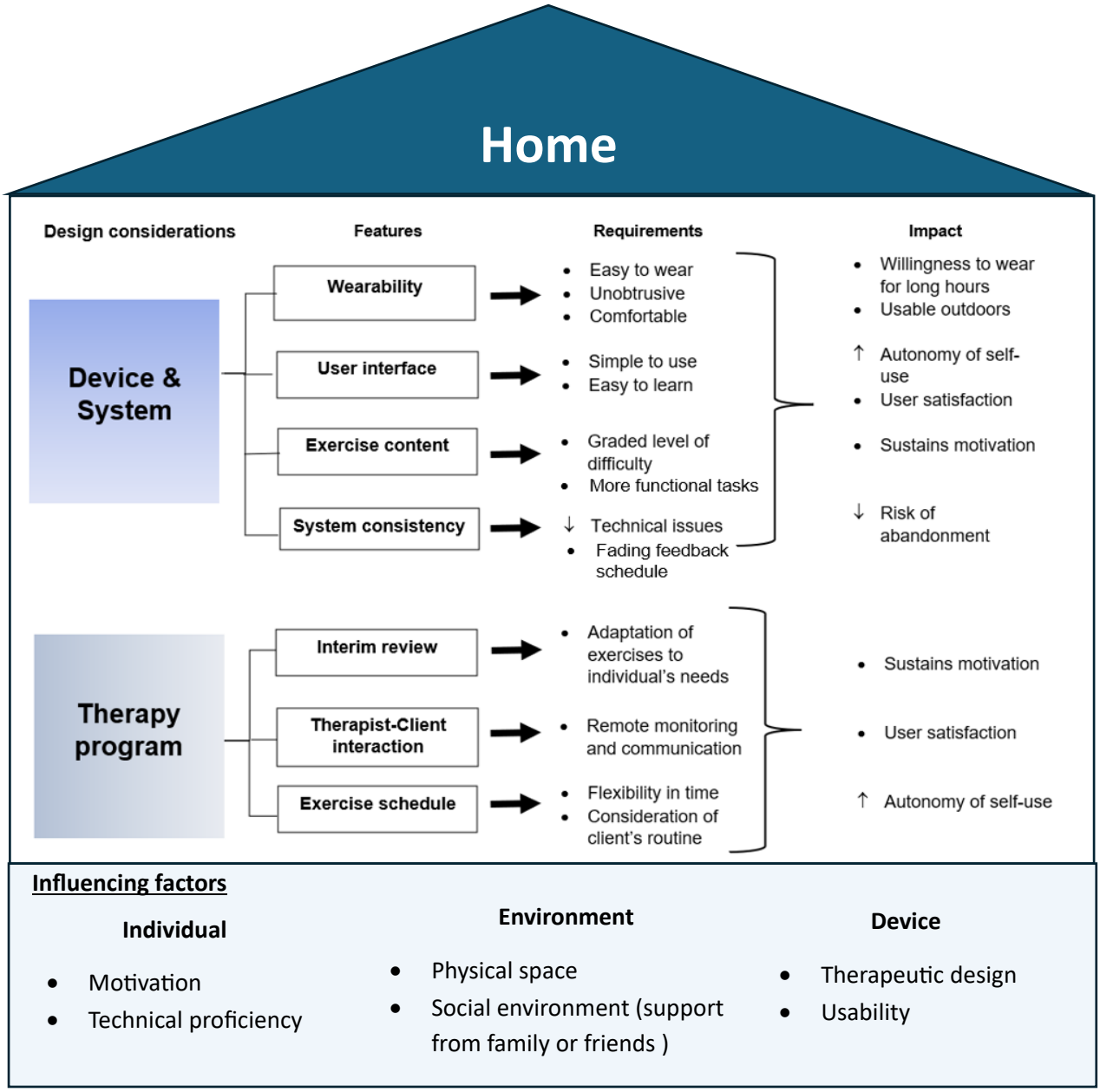
Findings from this PhD thesis underscore the importance of close therapist-to-client interactions that interim reviews, remote communication, and monitoring can support. Regular face-to-face or online monitoring with a therapist remains crucial in upper limb training, as 'learned non-use' (Raghavan, 2015) may lead participants to adopt compensatory movements.

The therapist's oversight is essential for correcting these compensatory movements and ensuring that stroke survivors perform their exercises correctly. Therefore, the intervention protocols in both clinical trials (Studies 4 and 5) include a weekly review with a therapist to support proper technique and optimize rehabilitation outcomes. Moreover, the participants in this PhD thesis research emphasized a need for high autonomy when using wearable technology, such as flexibility in their exercise schedule and location.

The SR device supports such flexibility because its telerehabilitation interface is supported by a mobile phone application, and the therapist can easily adjust the exercise schedule. Another clinical implication was that participants with different levels of UL severity might benefit differently from the augmented feedback provided by wearable devices such as the SR. Application of the wearable-based intervention for individuals with moderate to severe UL paresis (i.e., patients who have FMA-UE scores ranging from 17 to 46) appears to yield a relatively more favorable motor improvement, according to the main RCT study in this thesis research.

A current challenge in using wearables for healthcare is the issue of interoperability—that is, the question of how the wearable technology system can be integrated with the current system of telerehabilitation and other kinds of smart home technologies. In the future, the Smart Reminder app should not be singled out for use alone—instead, it can be designed as part of a comprehensive and universal mobile e-health platform accessible by the widest possible array of users, tailored on the basis of their abilities, and with additional beneficiaries for stroke rehabilitation.

Figure 7 -1: Summary of considerations for the design of a wearable technology-based intervention for home-based rehabilitation of stroke patients with upper limb hemiparesis



Previous studies (Adie et al., 2017; Chen et al., 2019) have highlighted the critical role of digital literacy in stroke patients, noting its impact on their motivation and acceptance of technology-based interventions. A user interface that is simple and easy to navigate within the e-health platform can help address this challenge and support users with varying levels of digital literacy. Therefore, a key consideration in designing a comprehensive e-health platform is to ensure that the user interface is intuitive and easy to use.

7.4 Limitations of the research and recommendations for future research

This PhD research had certain limitations. First, the main RCT study (Study 5, Chapter 6) adopted stratified convenience sampling and did not include participants with very severe hemiparesis (FTHUE-HK level of 2 and below). Hence, the results of this study cannot be generalized to all types of strokes throughout the population. A large-scale, randomized, multicenter study can be envisaged for future studies. One intention of using technology-based interventions, such as telerehabilitation in the home, is to reduce the need for direct contact with a therapist, thereby saving manpower costs. However, the main RCT study conducted in this PhD research focused on the clinical effects of intervention provided by the SR rather than on its economic value. Future studies can evaluate the economics of the SR intervention to assess its cost-effectiveness.

One limitation of the current SR device was that it could only support "prescribed therapy," such as telerehabilitation, and it could not track the amount of hemiplegic arm use by the stroke participants in their daily routines outside of therapy. A wearable device with dual functions—for example, for training and also monitoring, such as supporting the prescribed therapy and tracking the hemiplegic arm's use in the stroke survivors outside of therapy—would be ideal for encouraging intensive use of the affected UL in an individual's daily routine to sustain the therapeutic gains (Toh, Fong et al., 2023). Future studies could consider harnessing the full

potential of wearable sensors and developing a wearable device with these two functions. Neuroplasticity principles by Kleim and Jones (2008) indicated that training needs to be task specific. More functional tasks can be added in the exercise content of the SR telerehabilitation for task specific training so that stroke survivors can eventually transfer these skills in their daily activities.

Finally, the studies in this thesis have evaluated the participants on the basis of their observable motor outcomes of the hemiplegic upper limb, whereas changes in the participants' neuroplasticity after undergoing the SR intervention remain unclear. Future studies could explore the neuroplasticity effects of the SR intervention in persons with stroke, using neurophysiological prognostic biomarkers such as assessment of the motor-evoked potential detected using transcranial magnetic stimulation (TMS) and event-related desynchronization in task-related electroencephalography (EEG) or neural activation through T1- and T2-weighted imaging for motor connectivity over the ipsilesional and contralesional hemispheres in routine MRI techniques (Zhang et al., 2023), at baseline and post-treatment.

7.5 Conclusions

This PhD thesis research has identified the critical elements required to implement a technology-based intervention for successful upper limb rehabilitation in the home for people with stroke. It has also updated the current evidence on the application of wearable technology for stroke rehabilitation in the home. The thesis summarizes several key considerations for the design of a wearable technology to support home-based UL rehabilitation for persons with stroke. Furthermore, this thesis research designed, modified and tested a novel wearable device called the Smart Reminder and its interactive interface by following a human-centered approach that focused on the needs and requirements of the users of home-based stroke

rehabilitation methods (Rodgers et al., 2019). Two clinical trials conducted as part of this PhD research confirmed the efficacy of the telerehabilitation program provided by the SR in improving the motor outcomes of the hemiplegic UL for persons with stroke. This thesis sheds light on a new kind of stroke therapy and telerehabilitation that uses wearable technology in the home.

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