Understanding the Relationship Between Sleep and Motor Function After Stroke



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Abstract

Sleep plays a critical role in neuroplasticity. Therefore, it may influence motor function following stroke. Although evidence suggests a connection between sleep and motor function, this relationship remains inconclusive. Sit-to-walk movement is an essential part of independence in daily life. However, it is rarely investigated. Yet, it offers detailed motor function insights through fluency metrics (coordination, hesitation, and smoothness).

The main research aim of this project is to understand the relationship between sleep and motor function, with motor function measured by fluency metrics derived from STW (Third Study). The second aim is to assess the test-retest reliability of these metrics in non-stroke population (Second Study). A systematic literature review was conducted to synthesise the existing evidence regarding this relationship (First Study).

The systematic review results indicate a modest correlation between sleep and motor function, potentially limited by the heterogeneity of study methodologies.

The Second and Third studies were then carried out in parallel. The second study examined the fluency metrics of the sit-to-walk movement in non-stroke participants and compared them with data from stroke patients. The results demonstrate variable test-retest reliability; the confidence interval fell below the threshold for acceptable reliability (ICC < 0.75) for all variables, indicating low repeatability of measurements. Significant differences were observed in all biomechanical variables between the stroke and non-stroke groups, except for one of the coordination parameters.

The third study investigating the relationship between motor function and sleep found multiple correlations. After controlling for age, gender, and mental health in the linear model, average sleep bouts were the most strongly related sleep variable, followed by sleep quality measured by a Likert scale, time in bed, sleep efficiency, and the Pittsburgh Sleep Quality Index (PSQI).

Biomechanical measurements hold promise in clarifying the link between sleep and motor function by capturing motor function in greater detail. However, the variability observed in

fluency metrics during sit-to-walk movements underscores the need for research to verify their reliability.

Lay Summary

Sleep is important for brain neuroplasticity, which is the brain's ability to change and adapt. It's like the brain's way of rewiring itself to become more efficient or to compensate for damage, such as a stroke. Therefore, sleep may influence recovery after a stroke, which can affect a person's ability to move. There is some evidence linking sleep to movement abilities after a stroke, but the connection is not yet clear. Movement abilities are often measured using scales that may allow people to compensate for their impairments.

This project explored how sleep might influence the recovery of movement after a stroke, focusing on a specific everyday movement called the "sit-to-walk" (where you stand up from sitting and start walking). This movement is crucial for independence but has not been studied much in stroke recovery. It provides valuable insights into regaining movement abilities by measuring how smooth, coordinated, and fluent the movement is.

In detail:

Coordination: How well your body parts work together during a movement. In this study, knee and hip movements were investigated during the movement.

Hesitation: Pauses or delays during a movement. In this study, slowing down briefly after standing up before walking was measured.

Smoothness: How fluid and natural the movement looks, without jerks or awkward stops.

The main aim of this project is to explore how sleep affects regaining movement abilities, measured by the smoothness and fluency of the sit-to-walk (STW) movement (Third study), and to understand the relationship between sleep and stroke recovery. The first step was a review of existing studies to summarise what is already known about this relationship (First study). Then, the reliability of these measurements was tested in healthy individuals (Second study).

The results of these studies are as follows:

First Study (Review of Existing Research):

Past studies were reviewed and found some evidence linking better sleep to improved motor function after a stroke. However, the results were mixed, likely because different studies used different methods.

Second Study (Testing Measurement Reliability):

Healthy individuals were tested in terms of how consistent the measurements of the sit-to-walk movement were over time. It was found that the results within the same person, over a short period of time, varied too much to be considered repeatable.

Third Study (Exploring Sleep and Movement Abilities):

The third study explored how sleep affects regaining movement abilities after a stroke. It found several connections. After accounting for factors like age, gender, and mental health, the most important sleep factor linked with movement function was the number of uninterrupted sleep periods. Other important factors included overall sleep quality, time spent in bed, how long someone slept compared the time spent in bed, and scores from a sleep quality survey .

Overall, the study suggests that sleep is important for movement function after a stroke and measuring movements like sit-to-walk in detail could help us understand this relationship better. However, the tools used to measure these movements need improvement to ensure they are reliable. This research highlights the potential of combining sleep and movement analysis to improve stroke recovery strategies.

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Writing this part of my thesis has been unexpectedly emotional. Unlike my master's thesis, where I wrote only three sentences, I now find myself compelled to express more of what this journey has meant to me. My supervisor, Professor Valerie Pomeroy, often says, *"Merve, a PhD is not only about doing research; it is about learning how to be an independent researcher."* For any PhD students reading this, I believe that outlook is invaluable. During this journey, repeating steps, facing uncertainties, and not always knowing what lies ahead are all part of the learning curve. It can feel unsettling to lack clear direction, but I have come to see that a PhD is an experience we grow through. Much of its difficulty lies in the uncertainties we carry with us until the very end.

First and foremost, I want to thank myself—for being resilient, for standing up each time I fell, for confronting challenges head-on, and for knowing when to adapt. This perseverance has been essential, along with a dash of curiosity, in bringing me here.

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Teşekkürler Bölümü – Turkish Translation of Acknowledgement

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Bu kısmın hâlâ akademik bir bağlamda olduğunu biliyorum, fakat aynı zamanda düşüncelerimi de paylaşabileceğim bir zemin olarak düşünüyorum. Danışmanım Valerie Pomeroy her zaman bana, “Merve, doktora sadece araştırma yapmakla ilgili değil, aynı zamanda bağımsız bir araştırmacı olmayı öğrenmekle de ilgili” derdi. Bunu okuyan başka doktora öğrencileri varsa, bence bu bakış açısı çok kıymetli. Öğrenme sürecinde bazı adımları birkaç kez tekrarlamak, tam olarak ne yapacağını bilmemek tamamen normal. Ve zor kabul edilen bir his olsa da, birçok doktora öğrencisinin kendini böyle hissettiğinden eminim; ne durumda olduklarını, iyi mi kötü mü yaptıklarını, projenin geri kalanını nasıl yöneteceklerini bilmeden veya emin olmadan yola devam etmek çok zor. Fakat anladığım kadarıyla doktora, yolda öğrenilen bir şey. Doktoranın zorluklarının çoğu da bu belirsizlikten geliyor ve son noktaya kadar taşınması gereken ağır bir yük bu belirsizlik. Dolayısıyla, bu bölüme ilk olarak kendime teşekkür ederek başlamak abartı olmaz diye düşünüyorum: inatçı bir kız olarak her düştüğümde ayağa kalktığım, zorluklarla savaştığım ve bazen bu zorluklara uyum sağladığım ve en çok da kendim olmaya çalıştığım için kendime teşekkür ediyorum. Bugün burada olmamın nedeni bu. Belki biraz da merak 😊.

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kadar teşekkür etsem az; önce ona, sonra da bana inandığı için ve kendi deyimiyle girdiğim her sınava kendi giriyor gibi hissettiği için anneme teşekkür ederim. Akademik başarım, çocuklarına daha iyi bir gelecek sunmak isteyen inatçı bir adamın bu kararı sayesinde filizlendi diyebilirim. Teşekkürler, anne ve baba... Ve tabii ki doğduğum andan itibaren dostum oldukları için kardeşlerime de teşekkür ederim. Sizsiz bir hayat düşünemiyorum, umarım tecrübe de etmem. Bir de artık aramızda olmayan, ama huzurlu hissetmeye ihtiyacım olduğu zaman kendimi hâlâ evinde hayal ettiğim, ikinci annem olan anneanneme teşekkür etmek istiyorum. Seni her zaman sevgiyle hatırlayacağım; yalnız bana değil mezarının başındaki torunlarından ve çocuklarından oluşan 50 küsur insana; ellerinle dikip suladığın ve arkada bıraktığın meyve ağaçlarına kadar uzandı sevgin. Teyzelerime de teşekkür etmek istiyorum; doktora yaparak "evlenmek ve çocuk sahibi olmak yerine en iyi yıllarımı harcadığımı" düşünseler de, içten içe benimle gurur duyduklarını biliyorum. İsimlerinin hakkını vererek benim için anne yarısı oldular ve kuzenlerim de kardeş yarısı.

Bunların öncesinde, Atatürk'e, Türk Cumhuriyeti'nin kurucusuna teşekkür etmem gerektiğini düşünüyorum. Tüm yaptıklarının yanı sıra, köyde doğan bir kızın İngiltere'de doktora yapabilmesini sağlayacak bir toplumsal devrim yaptı. Ayrıca bu geleneği sürdüren ve burada eğitimime devam etme şansı veren Türkiye Cumhuriyeti devletine de teşekkür etmek istiyorum. Herkes gibi ülkem için endişeleniyor ve daha iyi günler görmeyi diliyorum, umarım iyi bir eğitim yalnızca zenginlerin erişebileceği bir lüks haline gelmez. Umuyorum ki, bayrağımızdaki yıldız gibi parlak bir geleceği görebiliriz.

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Impact of COVID-19 on PhD Research Project

COVID-19 profoundly impacted the PhD project and the broader research experience. These impacts were grouped as lab closures, changes in the study protocols and ethics applications, and disruptions to the research environment and my mental health.

The PhD project commenced on 1 January 2020, three months before the COVID-19 outbreak. The project's details were refined in the initial three months, initially focusing on acute stroke patients recruited from the NHS. During this time, preparations for the NHS ethics application were also undertaken. The aim was to examine motor function, sleep patterns, activity and stroke-specific information to elucidate recovery mechanisms and develop predictive models. For this aim, initial assessments were planned for the first two weeks following the stroke, with follow-up evaluations at three and six months to facilitate tracking of recovery progress. Along with project refinements, training was provided on the Vicon software, and research skills training sessions were attended. The office environment was vibrant and collaborative.

In early March, I travelled to Turkiye for my brother's wedding, intending to stay for two weeks. However, due to unexpected flight cancellations, my stay was extended until 16 June. I returned to the UK on the earliest available flight. During this period, I continued to work on my PhD remotely. Unfortunately, the environment in my family home in Turkiye was not conducive to focused academic work; because of the closure of schools and workplaces, all family members were home, leading to a crowded and distracting atmosphere. Additionally, I faced uncertainty regarding my return to the UK and the security of my sponsorship, which added significant stress to the situation. Meanwhile, the MoveExlab was closed due to a lockdown from 18 March to 1 September 2020.

During lockdowns, it became clear that obtaining NHS ethics approval amidst the health crisis would be challenging. Consequently, significant changes were implemented to the project. Instead of focusing on acute stroke patients, it was decided to enrol community-dwelling stroke patients from all over the phases. The study focus shifted from constructing a predictive model and investigating factors affecting early recovery to understanding the relationship between sleep and motor function. For this aim, polysomnography assessments in the sleep lab were initially planned; however, due to COVID-19 restrictions

and participants' reluctance to spend nights in a lab, sleep was measured instead through actigraphy watches. Additionally, a test-retest reliability study was planned to assess fluency metrics from the sleep and stroke study. However, due to COVID-19 limitations, we predicted we could not recruit age-matched non-stroke participants. Therefore, no age restrictions were applied. These changes were incorporated into the revised ethics application.

The lab reopened on 1 September 2020, becoming one of the first in the university to do so, but under strict protocols. Additional training was completed to ensure compliance with new regulations, and software training along with marker placement skills was refreshed due to the time elapsed since the initial training. The recruitment of participants started on 22 November 2020. However, it faced significant delays due to health and safety protocols, which limited lab occupancy and required extensive cleaning before and after each session. Recruiting participants also proved challenging due to apprehension around close contact.

Another closure was necessitated by the emergence of a new COVID-19 variant from 16 December 2020 to 12 March 2021. Following this closure, data collection resumed on 12 May 2021 but continued slowly, as lab access was limited to one participant per day to mitigate transmission risks. Scheduling difficulties also arose as the lab was in high demand due to other projects delayed by closures.

In addition to these disruptions affecting human-based research like this study, COVID-19 had a profound effect on the research community. More importantly, the isolation and challenges imposed by the pandemic deteriorated my mental health. A sense of "normalcy" was only gradually restored over nearly three years, eventually allowing activities that fostered research community engagement to resume, such as working in the postgraduate office, interacting with new researchers and attending face-to-face training sessions.

The PhD project was significantly changed by COVID-19: study protocols were reshaped, lab access was limited, and the collaborative research environment was disrupted. These challenges tested my resilience and adaptability, emphasising the struggles of pursuing research through a global crisis.

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Glossary

2D	Two Dimensions
3D	Three dimensions
6-MWT	6-minute Walking Test
ACT-1	Actigraphy data that processed based on sleep and wake times recorded in the sleep diary
ACT-2	Actigraphy data that processed solely based on light and activity data from the actigraphy
ADL	Activity of Daily Living
ARAT	Action Research Arm Test
Avg Wake B.	Average Wake Bout Duration
BBS	Berg Balance Scale
BCOM	Whole-body Centre-of-Mass
b-DAS	Brief Dimensional Apathy Scale
BI	Barthel Index
BOS	Base-of-support
BRS	Brunnstrom's Recovery Stage
C1	Coordination-1
C2	Coordination-2
CASP	Critical Appraisal Skills Programme
CBTi	Cognitive Behavioural Therapy for Insomnia
CoM	Centre of Mass
CSA	Central Sleep Apnoea
CSD	Consensus Sleep Diary
CV	Coefficient of Variation
DIS	Difficulty of Initiating Sleep
DMS	Difficulty Maintaining Sleep
DSM-IV	Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition
EEG	electroencephalography
ESS	Epworth Sleepiness Scale
FAC	Functional Ambulation Category
FMA	Fugl-Meyer Assessment
FMA-LE	Fugl-Meyer Assessment for Lower Extremities
FMA-UL	Fugl-Meyer Assessment for Upper Limb
GAD-7	General Anxiety Disorder-7
GI	Gait Initiation
GLM	General Linear Regression
HI	Hesitation Index
ICC	Intra-class Correlation Coefficient
ICF	International Classification of Functioning, Disability and Health
IS	Ischemic Stroke
ISI	Insomnia Severity Index
IU	Intervention Unit
JBI	Joanna Briggs Institute
K-BBS	Korean version of Berg Balance Scale
KSS	Karolinska Sleepiness Scale

MAS	modified Ashworth Scale
MoveExLab	Movement and Exercise Laboratory
mRS	modified Rankin Scale
N	Sample Size
N1	Superficial Sleep Stage
N3	Deep Sleep Stage
NIHSS	the National Institutes of Health Stroke Scale
Non-REM	non-Rapid Eye Movement
NOS	Newcastle-Ottawa Scale
OSA	Obstructive Sleep Apnoea
PECO	Population, Exposure, Comparator, Outcome
PHQ-9	The Patient Health Questionnaire
PPE	Personal Protective Equipment
PSF	Post-stroke fatigue
PSG	Polysomnography
PSQI	Pittsburgh Sleep Quality Index
QOS	Quality of Sleep, assessed by a question “how was your quality of sleep” and rated on a Likert scale from 1 to 9, higher values as worse sleep.
RCTs	Randomised Controlled Trials
REM	Rapid Eye Movement
RoB 2.0	Risk of Bias in randomised Studies 2nd version
ROBINS-E	Risk of Bias in Non-randomized Studies - of Exposures
ROBINS-I	Risk of Bias in Non-randomized Studies - of Interventions
S.diary	Sleep Diary
SD	Standard Deviation
SDB	Sleep-disordered Breathing
SDC	Smallest Detectable Change
SE	Sleep Efficiency
SEM	Standard Error of Measurement
SI	Suicidal Ideation
SOL	Sleep Onset Latency
SPARC	Spectral Arc Length method
SQS	Sleep Quality Scale
SSS	Stanford Sleepiness Scale
STS	Sit-to-Stand
STW	Sit-to-Walk
SWS	Slow-Wave Sleep
TIB	Time in Bed
TMS	Transcranial Magnetic Stimulation
TST	Total Sleep Time
WASO	Wakefulness After Sleep Onset
WMFT	The Wolf Motor Function Test

1 Chapter 1: Introduction

1.1 Stroke

Stroke is a severe neurological event that is the leading cause of disability and morbidity globally (Bernhardt *et al.*, 2017). In 2021, it is accounting for 5.6% of disability-adjusted life years and 10.7% of all fatalities (Feigin *et al.*, 2024). Stroke occurs when the brain's blood supply is disrupted, leading to the death of neural tissue (Yu *et al.*, 2016). Related to topography of brain tissue injury, it may lead to paresis, numbness, speech difficulties, vision impairment, and poor coordination. All these are common clinical symptoms of a stroke (Wlodarczyk *et al.*, 2021).

According to the Institute for Health Metrics and Evaluation, almost a million new instances of stroke are reported in Europe annually. However, less than 15% of survivors recover completely (Vos *et al.*, 2020). Globally, from 1990 to 2021, the incidence of new strokes rose by 70%, while the number of people experiencing stroke related health impacts increased by 32% (Feigin *et al.*, 2024).

Most stroke survivors live with persistent impairments. This creates a substantial long-term burden on caregivers and healthcare systems. The estimated annual cost of treating and caring for stroke patients in the 27 European Union nations was €27 billion in 2019, of which €18.5 billion are direct medical expenses and €8.5 billion are indirect costs such as loss of productivity (Rajsic *et al.*, 2019). Due to the ongoing increases in life expectancy, these expenditures will likely follow an upward trend (Marini *et al.*, 2004).

1.2 Post-Stroke Recovery and Neuroplasticity

Stroke is a disruption of blood flow to the brain, resulting in impaired brain function, especially in motor control, which causes disability. (Yu et al., 2016). In response to this injury, the brain activates cellular and molecular events including injury-induced neuroplasticity to support neural protection and encourage spontaneous recovery. Neuroplasticity refers to changes in the structure and function of neural networks in response to experiences, events, or stimuli. Clinically, this refers to changes in the brain following an injury.

Studies highlight several mechanisms of neuroplasticity to promote recovery: growth of synapses and dendrites, axonal sprouting and remodelling, angiogenesis, and increased expression of growth-related genes (Carmichael, 2003; Marín-Medina *et al.*, 2024). Brain excitability is increased correspondingly to these changes to accelerate neuroplasticity (Cassidy and Cramer, 2017).

Previously believed to be restricted to adulthood, neuroplasticity is now known to exist throughout life. However, after brain injury, including stroke, these changes occur rapidly and spontaneously soon after the stroke and typically plateau 3-6 months later (Hara, 2015; Dąbrowski et al., 2019). Recovery timeline based on neuroplasticity can be grouped into three epochs (Sophie Su, Veeravagu and Grant, 2016):

The initial damage after stroke leads to cell death and the loss of certain cortical pathways associated with the affected neurons (Sophie Su, Veeravagu and Grant, 2016). The first epoch starts hours after injury and lasts days. These early days present an opportunity to rescue threatened tissue, typically through reperfusion or neuroprotective measures (Cassidy and Cramer, 2017). Meanwhile, secondary neuronal networks are activated to sustain brain function (Sophie Su, Veeravagu and Grant, 2016).

The second epoch begins after the first phase and lasts for several weeks (Cassidy and Cramer, 2017). During this period, supportive brain cells are recruited, and cortical pathways change from inhibitory to excitatory states, facilitating synaptic plasticity and forming new connections (Sophie Su, Veeravagu and Grant, 2016). In the weeks to months that follow, the brain continues to remodel itself through axonal sprouting and further reorganisation around the damaged areas (Sophie Su, Veeravagu and Grant, 2016). Brain repair mechanisms and spontaneous recovery drive the reorganisation and regeneration of damaged neurons and neural pathways, with these natural recovery processes peaking during this time, allowing for significant functional improvements (Cassidy and Cramer, 2017).

The third epoch represents a stable period where repair processes continue slower, yet structural and functional brain modifications remain possible (Cassidy and Cramer, 2017). These adaptations are not limited to the area directly impacted by the stroke but also affect

connected regions in both hemispheres and even the spinal cord (Cassidy and Cramer, 2017).

This recovery timeline, detailed in three epochs, aligns with the five phases of stroke recovery defined by The Stroke Roundtable Consortium. The first epoch corresponds to the **hyperacute phase** (the first 24 hours) and **acute phase** (the first seven days). The second stage aligns with the **early subacute phase** (the first three months), while the third stage includes the **late subacute phase** (months 4–6) and the **chronic phase** (from 6 months onward). However, the recovery timeline following a stroke is flexible. It can vary based on individual factors such as the severity and location of the stroke (Sophie Su, Veeravagu and Grant, 2016; Bernhardt *et al.*, 2017).

1.3 Promoting Neuroplasticity for Motor Function

Neuroplasticity is the primary mechanism driving both spontaneous recovery and improvements gained through rehabilitation and neuromodulation techniques (Cramer, 2008; Hara, 2015; Cabral et al., 2022). By promoting neuroplasticity, recovery outcomes can be improved by engaging in meaningful, repetitive, intensive, and goal-oriented task-specific training. This approach focuses on practising real-life motor tasks directly related to everyday activities. Task-specific training encourages motor learning and cortical reorganisation. Therefore, it aids recovery by fostering adaptive neuroplasticity (Takeuchi and Izumi, 2013).

In recent years, substantial evidence has highlighted the critical role of sleep in neuroplasticity, particularly with neural network reorganisation, which is essential for learning and memory (Catherine F. Siengsukon and Boyd, 2009; Couyoumdjian *et al.*, 2010; Al-Sharman and Siengsukon, 2014). The connection between motor skill training and subsequent sleep patterns suggests that practising new motor skills can positively influence sleep, improving memory consolidation and cognitive function (Duss *et al.*, 2017). Meanwhile, Healthy sleep supports neuroplasticity, enhancing cognitive abilities and facilitating motor skill acquisition (Siengsukon and Boyd, 2009; Duss *et al.*, 2017). Therefore, sleep enhancement has emerged as a promising intervention to foster brain recovery after stroke and recent research has focused on investigating the effect of sleep on stroke recovery (Khan *et al.*, 2017; Mensen *et al.*, 2019; Rahayu *et al.*, 2020).

Consequently, in rehabilitation, task-specific training plays a critical role in promoting neuroplasticity and improving motor outcomes, and sleep can affect this process or vice versa (Duss *et al.*, 2017). Poor sleep may interfere with neuroplasticity mechanisms and cause poor recovery (Duss et al., 2017). Understanding this impact requires a clear distinction between *outcomes* and *recovery*, as they address different dimensions of progress after a stroke. Outcomes refer to the ability to complete a specific task, and outcome measurements mainly focus on task accomplishment. In comparison, recovery extends beyond task completion to encompass movement quality and neural pathways' reorganisation (Kwakkel et al., 2019). Motor outcomes can be achieved by restoring functional motor quality and/or through adaptive strategies such as behavioural compensation (Levin, Kleim and Wolf, 2009; Kwakkel *et al.*, 2023).

Behavioural restitution, often refers as true recovery, involves restoring pre-stroke movements and functions in the affected limb (Kwakkel *et al.*, 2023). In contrast, compensation entails adopting new movement strategies that differ from the original ones. It is characterised by gaining functional outcomes via bypassing impairments caused by the stroke (Cirstea and Levin, 2000; Kwakkel, Kollen and Lindeman, 2004). Reliance on adaptation and compensation may benefit short-term recovery gains but may hinder long-term motor recovery by reinforcing abnormal movement patterns (Nudo, 2013).

1.4 Motor Recovery for Independent Mobility

The ICF defines *mobility* as the capacity to move by altering body position or location or shifting objects from one place to another. This definition also encompasses key activities such as maintaining body position, walking, and transporting oneself (World Health Organization, 2024). Mobility after stroke primarily depends on regaining lower limb function and balance in standing and sitting (Langhorne, Bernhardt and Kwakkel, 2011) as these abilities are critical for independence and are often prioritised in stroke rehabilitation (Moore *et al.*, 2022). Cohort studies show that 80–95% of stroke survivors regain the ability to walk within 3–6 months, although this rate drops to 60% for those who cannot walk in the first week post-stroke (Jørgensen, Nakayama, Raaschou and Olsen, 1995; Jørgensen, Nakayama, Raaschou, Vive-Larsen, *et al.*, 1995; Verheyden *et al.*, 2008; Preston *et al.*, 2011).

Since walking is directly related to independent living, walking ability is the most studied functional outcome after stroke (Petrilli *et al.*, 2002). Another functional outcome essential for patient independence is the ability to stand up from a seated position, a prerequisite for walking (Pollock *et al.*, 2014)

1.5 Sit to Walk (STW)

Standing from a sitting position (Sit-to-Stand) usually follows gait initiation in daily life, occurring about 90% of the time in the healthy population and around 60% in stroke patients (Kerr *et al.*, 2017). If the rising transition is immediately followed by gait initiation, this movement is called sit-to-walk (STW) (Kerr *et al.*, 2017).

STW is especially essential during time-critical conditions, where an individual quickly transitions from sitting to walking, such as when answering a telephone or responding to an emergency (Buckley *et al.*, 2009). While STW is an essential activity of daily living (ADL), there is limited literature on its biomechanics, determinants, and characteristics (Kerr, Durward and Kerr, 2004).

The transition from sitting to walking is notably associated with a higher risk of falls among older adults and stroke survivors. Falls often result in improper weight shifting, tripping, and slipping in older adults due to balance issues (Robinovitch *et al.*, 2013). Moreover, older people are more likely to fall during weight-bearing and shifting activities, such as sit-to-stand and sit-to-walk (Pai *et al.*, 1994; Bestaven *et al.*, 2013). Not performing these activities due to fear of falling can also result in bodily and psychological decline, thereby increasing reliance on carers (Pozaic *et al.*, 2016; Xie *et al.*, 2018). Avoiding transitional activities is common among stroke survivors, who face even greater challenges in mobility and balance (Hyndman, Ashburn and Stack, 2002; Liu *et al.*, 2021).

Impairments after stroke also make it challenging for stroke survivors to perform these physical activities, such as turning while walking, executing transfers, and completing transition movements. (Forster and Young, 1995; Hyndman, Ashburn and Stack, 2002). Similarly, these limitations also increase the risk of falls during walking and transfer tasks (Schmid *et al.*, 2013). Consequently, a deeper understanding of the biomechanics and

contributing factors behind these movements is crucial to enhancing mobility and reducing fall risk in stroke survivors (Perera *et al.*, 2022).

The simplified biomechanics of the sit-to-walk (STW) movement involve rising from a stable seated position with three support points to standing on two feet. During this rising phase, the base-of-support (BOS) does not align perfectly with the body's centre of mass, causing temporary instability (Jones *et al.*, 2021). As walking begins, the BOS briefly reduces to one foot, the most unstable phase. This process combines the mechanics of sit-to-stand (STS) and gait initiation (GI), requiring precise balance and coordination through varying degrees of instability (Jones *et al.*, 2021) (Figure 1-1).

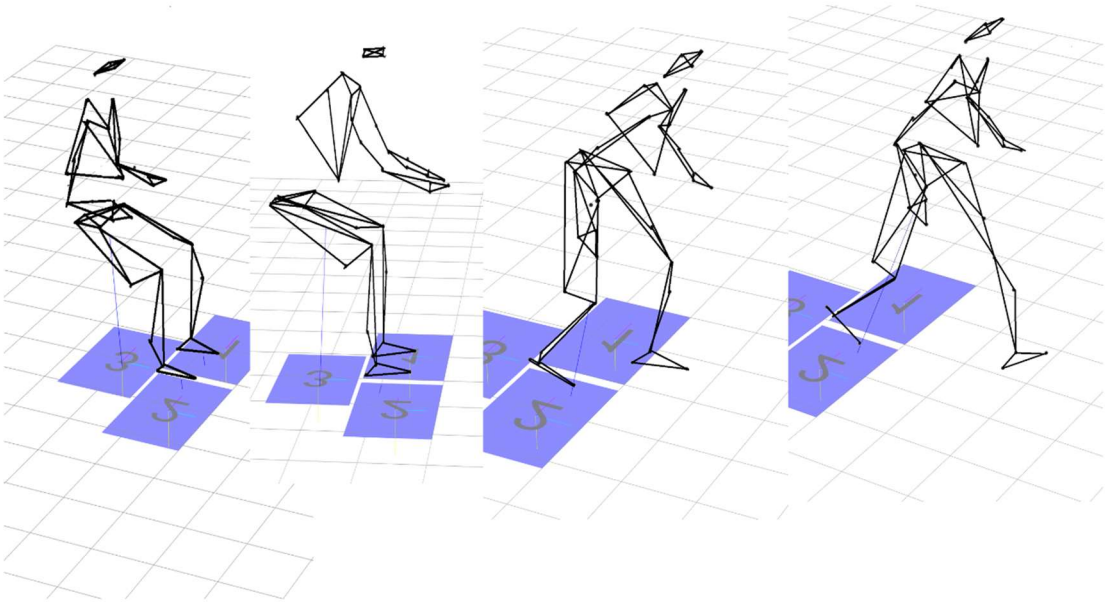


Figure 1-1 Sit-to-walk movement

STW movement is considered complex because it integrates sitting-to-standing (STS) and gait initiation around the seat-off event. This complexity is characterised by a reduction in whole-body centre-of-mass (BCOM) horizontal momentum immediately after seat-off (Buckley *et al.*, 2009). This reduction is used as a baseline measurement to assess hesitation. It is termed the "hesitation index" (HI), which quantifies the degree of momentum loss expressed as a proportion of the maximum momentum achieved during the rising action. (Malouin *et al.*, 2003; Kerr, Kerr and Durward, 2006). The hesitation index thus provides insight into the continuity of movement, where a larger HI value indicates

greater interruption or hesitation, potentially signalling less fluidity and more separation between STS and GI (Kerr *et al.*, 2017).

1.6 Evaluating Fluency Metrics in Sit-to-Walk to Measure Motor Function

Kerr *et al.* (2013) outline many fluency indices, including hesitation. According to this theory, normal movement is smooth, coordinated, and efficient, with minimal hesitation or repetition (Dion *et al.*, 2003; Kerr *et al.*, 2013). Thus, a practical definition of fluent movement must contain quantitative definitions for hesitation, coordination, and smoothness.

Movement hesitation is common in neurological and musculoskeletal disorders and has rarely been examined objectively. In the sit-to-walk (STW) movement, hesitation is quantitatively defined as a percentage decrease in the forward movement of the centre of mass (CoM) (Kerr et al., 2013).

Coordination is characteristic of normal, fluid movement in both the upper and lower extremities. However, it is frequently used generically and without quantifiable definitions. Objective coordination assessments have been developed using metrics based on the relative time of joint motions. Most assessments consider the temporal overlap between joint motions, with higher rates of overlap indicating more fluent movement as it indicates a synchronisation between knee and hip movements (Kerr et al., 2013). In STW, this is defined as the temporal overlap of flexion and extension movements in the knee and hip joints of the stance leg during two distinct phases.

The first phase, known as Coordination 1 (C1), occurs between the onset of knee extension and the completion of hip flexion. This phase involves the initial extension of the knee while hip flexion is also happening. The second phase, referred to as Coordination 2 (C2), occurs between the onset of knee flexion and the completion of hip extension. This phase encompasses knee flexion during gait initiation, while hip extension still continues (Kerr *et al.*, 2013; Chandler *et al.*, 2021). Kerr et al. (2013) demonstrated that non-stroke participants exhibited good coordination by starting gait while still in hip extension (raising). However, elderly people with fall risk demonstrated reduced coordination, so knee flexion

occurred after sufficient hip extension, resulting in an upright position based on these metrics.

Therapists frequently use movement smoothness to describe the quality of motor control. However, objectively defining and quantifying smoothness is challenging (Magnan, McFadyen and St-Vincent, 1996; Rohrer *et al.*, 2002). One approach is measuring smoothness by assessing the number of fluctuations in the jerk signal of the centre of mass (CoM), where a higher number of fluctuations indicates less smooth (i.e. more jerky) movement (Kerr *et al.*, 2013; Chandler *et al.*, 2021).

Another commonly used method to quantify smoothness is the Spectral Arc Length (SPARC) technique. (Balasubramanian *et al.*, 2015; Melendez-Calderon, Shirota and Balasubramanian, 2021). SPARC is recommended for measuring the smoothness of reach-to-grasp tasks following a stroke (Mohamed Refai et al., 2021) and applies to various movement types (Balasubramanian et al., 2015), which makes it a valuable tool for assessing smoothness in general motor tasks. This method has been successfully used to distinguish between gait smoothness in individuals with Parkinson's disease and healthy adults (Beck et al., 2018) and between elderly individuals at risk of falling and those not (Figueiredo et al., 2020). Given its versatility, SPARC could also be highly beneficial in assessing smoothness with other fluency metrics in the Sit-to-Walk (STW) task, which is an essential activity of daily living (ADL) that requires complicated postural and locomotor activities and relies mainly on balance regulation.

Understanding the precise biomechanics of STW can help design wearable assistive technologies and focused interventions, especially for older people and individuals with movement limitations. This could dramatically improve their mobility, independence, and quality of life. However, there is still a lack of sufficient research on STW techniques, biomechanics, and transitions, especially for these populations (Perera *et al.*, 2022). As such, further studies in this area are needed.

Stroke recovery research could benefit from incorporating fluency metrics derived from the STW as a measure of motor function. However, it is also essential to develop normative data that reflect the performance of neurologically healthy individuals to accurately assess motor function through kinematic analysis. These data provide a baseline for evaluating

stroke patients by representing the performance of a large group of healthy individuals across different ages, genders, and other factors (G Kwakkel *et al.*, 2019; Kwakkel *et al.*, 2023). Representative and diversified samples of hundreds of healthy people are needed to create normative models that adequately reflect the expected performance for any given demographic group (Scott *et al.*, 2023). Once developed, these normative models will remove the requirement to find age- and sex-matched control subjects for each study, allowing for accurate, tailored assessments of impairments (Scott *et al.*, 2023). With normative data established, fluency metrics can offer a more comprehensive evaluation of motor function in stroke patients. This is because kinematic analyses, including fluency metrics, allow for the measurement of true recovery progress without interference from compensatory strategies. As such, these metrics are recommended for accurately assessing motor function (Bernhardt *et al.*, 2017).

Considering the vast number of individuals who live with long-term impairments post-stroke, another crucial area for future research is exploring strategies that promote motor function (Vos *et al.*, 2020). Sleep emerges as a promising area for such research, given its strong influence on motor learning and neuroplasticity (Walker *et al.*, 2003, 2005; Facchin *et al.*, 2020).

1.7 Sleep

Sleep plays an integral role in a healthy life, as it supports homeostatic regulation and facilitates cellular repair mechanisms (Vyazovskiy and Harris, 2013). Therefore, the lack of sleep detrimentally affects the brain and the immune system. Extended sleep deprivation can cause neuron malfunction due to the interruption of specific patterns of electrical and chemical activity in the brain during sleep; this impacts the brain's ability to function normally (Krause *et al.*, 2017).

Sleep is not a uniform physiological state; it comprises two physiologically distinct vigilance states: non-rapid eye movement (non-REM) and rapid eye movement (REM). Non-REM sleep makes up 76-80% of the total sleep time (González-Naranjo *et al.*, 2019), and it is characterised by a general decline in physiological arousal levels, reduced mental activity, and some involuntary body movements. It also plays a vital role in the brain's cellular metabolic and synaptic restoration (Kalia, 2006). Based on electroencephalographic (EEG)

features, it consists of three stages ranging from superficial sleep (N1) to Deep sleep (N3), which is known for slow-wave sleep occurs in this deep sleep stage (González-Naranjo *et al.*, 2019). REM sleep is characterised by increased brain activity and physiological arousal levels comparable to alertness but with total paralysis of major body muscles. It is frequently linked to emotionally charged dreaming mentation. Although the purpose of REM sleep is less understood than that of non-REM sleep, it is known to have a part in memory consolidation and emotional control (Kalia, 2006).

1.8 Bidirectional Relationship between Sleep and Stroke

There is a bidirectional link between sleep disorders and stroke (Duss et al., 2017; Davis et al., 2019): Sleep disorders can alter vascular risk factors and elevate the risk of stroke (Mohammad *et al.*, 2019). On the other hand, brain network disturbances caused by a stroke can also affect sleep regulation and cause sleep disturbances (Duss *et al.*, 2017; Davis *et al.*, 2019). For example, stroke disrupts endogenous circadian rhythm markers; for example, post-IS, melatonin suppression is observed (Gottlieb *et al.*, 2019). The readmission of exogenous melatonin is found to have neuroprotective benefits in rodents. However, translating these experimental finding to the human stroke population remains uncertain (Gottlieb *et al.*, 2019).

This bidirectional relationship extends to motor function, where sleep disorders not only impede recovery but are also influenced by stroke-related impairments. There is growing evidence suggesting that stroke patients with sleep disorders tend to experience worse outcomes compared to those without sleep disorders (Kaneko et al., 2003; Fulk, Duncan and Klingman, 2020). A possible reason for this is that sleep plays a crucial role in memory consolidation and motor learning. Stroke patients who sleep well tend to execute newly acquired motor tasks with fewer mistakes (Siengsukon et al., 2015). Additionally, sleep disorders and poor sleep in stroke patients negatively impact various other brain-related outcomes. These include cognition, attention, anxiety, and depression (Pearce et al., 2016; Glozier et al., 2017; Li et al., 2019) which make it more difficult for individuals to actively engage in stroke rehabilitation. As a result, they are associated with poorer rehabilitation outcomes (Fulk et al., 2020).

On the other side of the relationship, stroke-induced motor impairment can exacerbate sleep disturbances by creating a feedback loop (Smith et al., 2024). Physical limitations often lead to reduced physical activity, which in turn contributes to poorer sleep quality (Ezeugwu and Manns, 2017). Stroke patients typically spend significant portions of their waking hours in sedentary behaviours (Rand et al., 2009). This inactivity negatively affects sleep hygiene and can exacerbate sleep disorders. In turn, these sleep issues further hinder recovery (Davis et al., 2019).

When examining the direct pathophysiological link, stroke can impair various aspects of respiratory function. It may disrupt central control of the respiratory drive and alter normal breathing patterns. Stroke can also compromise airway protection and impair the mechanics of both inspiration and expiration (Howard *et al.*, 2001; Rochester and Mohsenin, 2002). These disruptions can contribute to the development of sleep-disordered breathing. Sleep disturbances following acquired brain injuries may arise from multiple overlapping factors. These include direct damage to arousal-promoting neurons, injury or inflammation in regions like the cortex, thalamus, and hypothalamus, diffuse axonal injury, and altered cerebral energy metabolism (Sandsmark, Elliott and Lim, 2017).

The suprachiasmatic nucleus (SCN) functions as the central pacemaker of the circadian system by integrating internal and external cues (Cox and Takahashi, 2019) and synchronising peripheral molecular clocks throughout the body (Barclay, Tsang and Oster, 2012; Vujovic *et al.*, 2015). Although individual cells possess intrinsic circadian rhythms driven by transcriptional feedback loops, the SCN maintains temporal coordination via hormonal and autonomic signalling (Barclay, Tsang and Oster, 2012; Vujovic et al., 2015). This synchronisation process is influenced by zeitgebers such as light exposure and physical activity. Disruption of the SCN or reduced exposure to zeitgebers, for example post-stroke immobility or limited daylight exposure, can therefore lead to circadian misalignment and subsequent sleep disturbances (Zhang *et al.*, 2014).

There is growing evidence indicating that sleep disturbances, whether pre-existing or newly developed post-stroke, are so common among stroke survivors that almost half of stroke patients experience them (Deak, 2013). These disturbances are associated with poorer stroke outcomes and an increased risk of cardiocerebrovascular morbidity (Duss *et al.*, 2017). Some of the most common sleep disturbances associated with stroke are listed:

Obstructive Sleep Apnoea (OSA) is characterised by repeated episodes of partial or complete obstruction of the upper airway during sleep, which causes reduced or paused breathing. This situation also leads to fragmented sleep and a drop in blood oxygen levels, increasing the risk of cardiovascular issues (Sankri-Tarbichi, 2012). Obstructive sleep apnoea (OSA) is an established independent risk factor for stroke (Redline et al., 2010). On the other side of equation, its prevalence often increases during the acute phase. Moreover, it is associated with stroke recurrence and worse long-term outcomes (Brown *et al.*, 2020; Huhtakangas *et al.*, 2022).

Central Sleep Apnoea (CSA) differs from OSA because it is caused by the brain's failure to send proper signals to the muscles that control breathing rather than an airway obstruction (Sankri-Tarbichi, 2012). It is less common than OSA (Seiler *et al.*, 2019) and may develop de novo following a stroke. While its exact prevalence remains unclear, it is thought to predict higher mortality rates. Similar to OSA, it may improve during the chronic phase of stroke (Brunetti *et al.*, 2022).

Both OSA and CSA exacerbate brain injury by causing intermittent hypoxia and disrupting normal sleep architecture (Ramos, Seixas and Dib, 2015). This disruption typically causes decreased total sleep time, increased sleep fragmentation, and reduced slow-wave sleep (SWS). Moreover, this situation can indirectly heighten daytime sleepiness. As a result, the patient's ability and motivation to engage in rehabilitation can be adversely affected (Gooneratne *et al.*, 2011; Frohnhofen *et al.*, 2013).

Sleep Duration: In recent years, several studies have examined the effects of sleep durations that fall outside the recommended range, and they suggest that both insufficient and excessive sleep may be potential risk factors for stroke. Although the findings of individual studies have been inconsistent (Brunetti *et al.*, 2022), reviews and large studies enable us to draw better conclusions: A population-based study involving over one million participants found that both very short(≤5 h) and very long (≥10 h) sleep durations were linked to an increased risk of stroke (Lu *et al.*, 2020). A more recent meta-analysis of 20 cohort studies found a U-shaped relationship between sleep duration and stroke risk. It indicated that longer sleep durations are more strongly associated with stroke risk and mortality than shorter ones. (Wang *et al.*, 2022).

Sleep quality: More than half of stroke survivors report experiencing poor sleep; this high percentage is concerning for stroke patients. However, this estimate requires cautious interpretation due to high heterogeneity among studies (Luo *et al.*, 2023). A recent meta-analysis of polysomnography (PSG) studies in acute ischemic stroke found that stroke patients exhibit worse sleep quality than controls, specifically regarding sleep efficiency (SE) and wake-after-sleep onset (WASO) (Baglioni *et al.*, 2016). Improved sleep efficiency and reduced wakefulness after sleep onset in the acute phase were also linked with better long-term outcomes (Vock *et al.*, 2002). In the chronic phase, poor sleep quality remains highly prevalent and is closely linked to poorer recovery outcomes (Brunetti *et al.*, 2022).

Insomnia is characterised by difficulties in falling or staying asleep or experiencing non-restorative sleep despite having the opportunity to rest (Roth, 2007). It is considered a potential risk factor for stroke. Insomnia and fragmented sleep similarly impair stroke recovery by reducing sleep efficiency and limiting the duration of restorative sleep stages. Therefore, it can adversely impact cognitive functions and physical recovery capabilities (Gooneratne *et al.*, 2011; Frohnhofen *et al.*, 2013).

A retrospective study found that 28.6% of patients who developed insomnia following a stroke exhibited poorer functional and cognitive outcomes, as well as more severe neurological deficits, compared to those without insomnia (Matas, Amaral and Patto, 2022). A recent study indicates that post-stroke insomnia is linked to greater physical disability, increased dementia symptoms, and heightened anxiety (Leppävuori *et al.*, 2002). It also raises the risk of a subsequent stroke (Bassetti and Hermann, 2011; McDermott, Brown and Chervin, 2018). Furthermore, chronic insomnia is correlated with higher disability and mortality rates in post-stroke (Glozier *et al.*, 2017; Li *et al.*, 2018; Fleming *et al.*, 2021).

Hypersomnia is characterised by excessive daytime sleepiness or prolonged sleep periods. It is a core feature of bilateral thalamic stroke (Jaramillo *et al.*, 2021). In the chronic phase, hypersomnia may overlap with post-stroke fatigue, possibly leading to worse outcomes (Harris *et al.*, 2014). **Disruptions in circadian rhythm** have been identified as potential cerebrovascular risk factors; circadian misalignment increases the likelihood of stroke (Brunetti *et al.*, 2022).

Post-stroke fatigue is a prevalent and subjective condition characterised by persistent and intense feelings of fatigue, weakness, or exhaustion, which can affect both physical and mental functioning and is not alleviated by typical rest (Zedlitz *et al.*, 2012). Post-stroke fatigue is associated with several negative outcomes, such as impairing functional rehabilitation (Choi-Kwon *et al.*, 2005; Naess *et al.*, 2005; Lerdal *et al.*, 2011; Maaijwee *et al.*, 2015), affecting cognitive function (Maaijwee *et al.*, 2015), and increasing mortality (Glader, Stegmayr and Asplund, 2002; Naess *et al.*, 2005). The prevalence of fatigue in stroke survivors is notably higher than in the general population. Fatigue affects a significant proportion of stroke patients, with rates ranging from 32% in the acute phase (Duncan *et al.*, 2015; Wu *et al.*, 2015; Zhang *et al.*, 2022) to over 50% at 6 months or more (Choi-Kwon *et al.*, 2005; Winward *et al.*, 2009; Rahamatali *et al.*, 2021). In contrast, general fatigue in the broader adult population is reported at 20.4%, and chronic fatigue at 10.1% in a review totalling 623,624 participants (Yoon *et al.*, 2023).

When comparing the prevalence of sleep disorders in healthy individuals and stroke patients: Insomnia, which affects around 10% of healthy adults (Morin *et al.*, 2020), is reported in 40.7% of stroke patients during the acute phase, 42.6% in the subacute phase, and 35.9% in the chronic phase (Hasan *et al.*, 2021). Sleep-disordered breathing (SDB), prevalent in 50% of older adults (Rodriguez, Dzierzewski and Alessi, 2015), is significantly more common post-stroke, with rates of mild (66.8%), moderate (50.3%), and severe (31.6%) SDB in the acute phase (Hasan *et al.*, 2021). Restless leg syndrome, affecting 9.0% of women and 5.4% of men in the general population (Allen *et al.*, 2005), is seen in 10.4% of acute stroke patients and 13.7% in the chronic phase (Hasan *et al.*, 2021). Similarly, periodic leg movement disorder, which affects 0.04% of healthy individuals (Gulia and Kumar, 2018), occurs in 32.0% of acute, 27.3% of subacute, and 48.2% of chronic stroke patients (Hasan *et al.*, 2021).

Central disorders of hypersomnolence show varied prevalence in stroke patients. Narcolepsy, found in 0.04% of individuals in the general population (Acquavella *et al.*, 2020), occurs in 20%–40% of stroke patients (Kojic et al., 2022). Hypersomnia is reported in 1.1%–27% of stroke patients (Bollu *et al.*, 2017). For the healthy population, idiopathic hypersomnia is 10.3 per 100,000 persons (Acquavella *et al.*, 2020). Circadian rhythm sleep-wake disorders, with a prevalence of 0.13%–0.17% in the general population (Schrader,

Bovim and Sand, 1993; Yazaki *et al.*, 1999), have not been specifically studied in post-stroke patients.

However, some studies report significant circadian changes following ischemic stroke, correlating with stroke severity and recovery outcomes (Kantermann *et al.*, 2015). Parasomnias are common in the general population, with a lifetime prevalence ranging from 4% to 67% in adults. From these, nightmares, are the most common, affecting 66.2% of adults (Singh *et al.*, 2018). While no studies were found on the prevalence of parasomnias in post-stroke patients, one study reported that adults with REM behaviour disorder were 1.5 times more likely to develop stroke, independent of age, gender, hypertension, and tobacco (Kantermann *et al.*, 2015).

These findings underline the high prevalence of sleep disorders in stroke patients. Moreover, research suggest that sleep disturbances are not only prominent risk factors for stroke but also influence the course and outcome of stroke recovery (Brunetti et al., 2022). While the broader relationship between sleep and stroke is crucial to explore, this research specifically focuses on the impact of sleep on motor function. The following section will delve into the ways in which sleep influences recovery following a stroke.

1.9 How Sleep Affects Stroke Recovery

The relationship between sleep and recovery after stroke is supported by several studies examining neurophysiological and behavioural mechanisms. In humans, sleep following stroke is characterised by increased slow-wave and theta activity in the infarcted area of the affected hemisphere during sleep, observed in both the acute and chronic stages. Conversely, the peri-infarct area exhibited lower slow-wave, theta activity, and spindle power compared to the non-affected hemisphere. Changes in sleep slow-wave activity are linked to stroke severity and recovery, with both increases and decreases in specific brain regions associated with these outcomes. The persistent decrease in slow-wave activity over the peri-infarct area during sleep (but not wakefulness) suggests that cortical dysfunction in this region disrupts physiological sleep, likely hindering recovery processes associated with sleep (Poryazova *et al.*, 2015). In rats, sleep disruption after induced stroke worsens outcomes, increasing brain damage and hindering neural recovery by limiting axonal sprouting (Gao *et al.*, 2010).

Similarly, optogenetically induced slow waves during sleep enhance fine motor function and neural circuit remodelling in mice. At the same time, such stimulation during wakefulness has no effect, highlighting the critical role of sleep-specific activity in post-stroke recovery (Facchin *et al.*, 2020). Pre-clinical studies further highlight the importance of sleep, demonstrating that sleep deprivation following ischemic stroke (IS) is associated with larger lesion volumes. Furthermore, sleep deprivation before IS triggers compensatory rebound sleep, which has neuroprotective effects (Eguchi *et al.*, 2010; Gianfagna *et al.*, 2016).

1.9.1 Sleep and Neuroplasticity

Stroke disrupts cortical and subcortical circuits adjacent to the damaged area. Recovery involves reorganising and reallocating lost functions towards unaffected neurons; this process is facilitated by neuroplasticity (Gerloff *et al.*, 2006). The regulation of neuroplasticity is now known to be one of sleep's primary functions (Tononi and Cirelli, 2014; Yang *et al.*, 2014; Genzel *et al.*, 2015; De Vivo *et al.*, 2017; Gulati *et al.*, 2017; Klinzing, Niethard and Born, 2019).

There are various theories on how sleep boosts brain functions. However, the exact mechanisms linking sleep to brain reorganisation remain unclear (Born and Wilhelm, 2012). **Synaptic downscaling theory** suggests that SWS regulates synaptic connections activated during daytime learning by making neurons more easily stimulated and marking them with decreased electrical potentials (Tononi and Cirelli, 2014). **Active system consolidation theory** posits that sleep, especially during SWS, helps convert short-term memories into long-term ones by reactivating memory traces in the hippocampus and gradually transferring them to the neocortex for permanent storage (Born and Wilhelm, 2012). Consequently, sleep deprivation affects short-term memory, and the consolidation of long-term memories therefore hinders learning and memory consolidation. Despite not directly related to learning, **the energy allocation model** proposes that energy conservation during sleep supports biological processes like intracellular transport, membrane repair, and macromolecule biosynthesis (Duss *et al.*, 2017).

The initial evidence regarding the link between sleep and neuroplasticity originates from insomnia studies (Zhang et al., 2017): These patients displayed a reduction in grey matter

in some subregions of the prefrontal cortex (Altena et al., 2010; Joo et al., 2013), and they represented a smaller hippocampal volume (Riemann et al., 2007; Joo et al., 2014). In addition to neurological alterations, individuals with insomnia exhibit reduced sleep-dependent memory consolidation, which is regarded as a marker for neuroplasticity in procedural and declarative learning. (Backhaus et al., 2006; Nissen et al., 2011).

Furthermore, sleep seems to moderate motor learning, which is a critical mechanism in stroke rehabilitation. Although limited research has systematically investigated the effect of sleep on motor learning in stroke patients, findings suggest that sleep improves motor task performance (Siengsukon and Boyd, 2008; Catherine F. Siengsukon and Boyd, 2009). This effect is most likely the result of consolidation during sleep after motor skill exercises (Diekelmann and Born, 2010; Gudberg and Johansen-Berg, 2015; Christova *et al.*, 2018)

The impact of sleep on motor learning and neuroplasticity has prompted researchers to explore its role in the recovery process following a stroke (Gorgoni *et al.*, 2013): A recent study indicates stroke patients executed newly acquired motor tasks with reduced mistakes following a night's sleep. Moreover, longer duration of REM sleep correlated with better offline motor learning in stroke patients (Siengsukon *et al.*, 2015). These findings highlight the potential importance of sleep for memory consolidation in neurorehabilitation, which means that optimising sleep during rehabilitation could substantially enhance recovery (Duss *et al.*, 2017).

1.10 Exploring the Connection Between Sleep and Motor Function Recovery After Stroke

There is growing evidence suggesting that stroke patients with sleep disorders tend to experience worse outcomes compared to those without sleep disorders (Kaneko *et al.*, 2003; Fulk, Duncan and Klingman, 2020). The findings from the recent systematic review present mixed evidence regarding the impact of sleep disorders on physical function recovery and participation after stroke. Approximately half of the studies reviewed reported a notable difference in recovery outcomes between stroke patients with and without sleep disorders; in contrast, the remaining studies observed no such difference. However, a meta-analysis of all these studies provided a more precise picture: On average, stroke patients with sleep disorders tend to experience poorer recovery outcomes compared to those

without sleep-related issues. Specifically, individuals with sleep disorders scored about 10 points lower on the Barthel Index (BI) and 0.5 points higher on the modified Rankin Scale (mRS), suggesting greater levels of disability. These poor outcomes were observed in both stroke chronicity (<3 months poststroke vs ≥3 months), even when accounting for baseline stroke severity, which further illustrates the negative impact of disturbed sleep on stroke recovery (Fulk *et al.*, 2020). Additionally, sleep disorders and poor sleep in stroke patients negatively impact various other brain related outcomes, including cognition, attention, anxiety, and depression (Pearce *et al.*, 2016; Glozier *et al.*, 2017; Li *et al.*, 2019). These issues make it more difficult for individuals to engage actively in stroke rehabilitation, which further contributes to poorer rehabilitation outcomes. Consequently, they are linked to worse recovery results (Fulk *et al.*, 2020).

Another study on inpatient stroke rehabilitation found that poor sleep quality was linked to worse functional and motor outcomes (Fleming, Smejka and Slater, 2020). This study did not focus on any specific sleep disorder. Similarly, another research on stroke patients with disturbed sleep, but without a formal sleep disorder diagnosis, found that poor sleep was associated with reduced functional mobility and greater difficulty completing daily living activities (ADLs) (Bakken *et al.*, 2012; Moon *et al.*, 2018).

Evidence from the subacute phase of stroke suggests that sleep disruption impacts motor outcomes (Fleming, Smejka and Slater, 2020). However, only one study has compared sleep patterns between chronic stroke survivors and healthy controls. This study explored the relationship between sleep, motor impairment, mental health, and inactivity. It found that stroke survivors had significantly poorer sleep quality, but neither motor impairment nor time since stroke explained variations in sleep. Depressive symptoms, however, were linked to poorer sleep quality (Fleming *et al.*, 2021).

Further research is needed to explore how motor function, mental health, and sleep affect stroke recovery (Fleming *et al.*, 2021). Moreover, in the Fleming (2021) study, lower limb motor impairment could not be assessed due to logistical and safety constraints, leaving the question of whether lower limb motor function might be related to sleep quality during the chronic stage of stroke recovery.

Beyond its role in physical health, sleep is closely tied to mental health outcomes. A large meta-analysis on the impact of sleep on mental health found that improvements in sleep quality significantly enhanced mental health, including reductions in depression, anxiety, and stress (Scott *et al.*, 2021). Given this strong relationship, in this project, mental health assessments are incorporated to understand the interplay between motor function and stroke.

1.11 Measuring Sleep

1.11.1 Sleep Measurement Tools

Sleep can be assessed through various tools, which are essentially classed as objective or subjective assessments. Polysomnography and actigraphy are two objective test methods that provide quantitative data on sleep patterns and quality. On the other hand, subjective methods such as sleep diaries and sleep questionnaires rely on self-reported assessment. They record individuals' perceptions and experiences of sleep (Hoey, Fulbrook and Douglas, 2014; Sadeh, 2015).

Polysomnography (PSG) is a systematic method for collecting numerous physiological measures while the participant is in the bed and is commonly recognised as the gold standard in sleep assessment (Rundo and Downey, 2019). PSG is normally performed in a sleep laboratory and measures electrical brain activity, muscle tone, eye movements, and oximetry is used to monitor breathing and oxygen saturation during sleep (Hoey, Fulbrook and Douglas, 2014; Sadeh, 2015). This extensive equipment enables PSG to deliver the most detailed insights into sleep architecture. Even though it is the most accurate measure of sleep, PSG is expensive and impracticable for large-scale studies. Moreover, its highly controlled and intrusive setting may affect natural sleep patterns (Hoey, Fulbrook and Douglas, 2014; Sadeh, 2015).

Actigraphy is a simple and reliable alternative to polysomnography (PSG) for tracking sleep-wake rhythms (Ancoli-Israel *et al.*, 2003; Fekedulegn *et al.*, 2020). It uses wrist-worn watch-shaped devices to measure body movement. Actigraphy enables unobtrusive monitoring in natural settings as opposed to PSG, which requires a controlled environment and several sensors (Krishna and Mashaqi, 2014). However, it may be perceived as inactivity as sleep,

especially in situations with low-functioning hemiparesis and fragmented sleep. Therefore, subjective sleep diaries are required to improve accuracy (Laakso *et al.*, 2004; Fekedulegn *et al.*, 2020; Gottlieb *et al.*, 2021).

Sleep diaries collect subjective sleep data such as bedtimes, sleep duration, and night awakenings across multiple days, as well as daytime variables such as naps and coffee use. Although they represent a person's impression of sleep, they are considered less accurate than objective approaches, particularly for night awakenings (Vanable *et al.*, 2000; Kushida *et al.*, 2001; Means, 2003). Sleep diaries are susceptible to overestimation (Kushida *et al.*, 2001) and compliance concerns (Stone, 2002), but they provide valuable insights into reported sleep behaviour and supplement objective approaches (Chesson *et al.*, 2000; Sadeh and Acebo, 2002). Despite lacking an agreed-upon standard format, Carney *et al.* (2012) refer to sleep diaries as the "gold standard" for subjective sleep evaluation.

Questionnaires, like sleep diaries, collect subjective sleep ratings retrospectively and are widely used due to their simplicity and ease of administration. They evaluate numerous sleep and daily functioning habits and are appropriate to diverse groups, including people with sleep problems or chronic illnesses. Despite their low cost and ease of use, subjective assessments may be inaccurate due to experimenter bias and poor self-perception (Harvey *et al.*, 2008; Robert and Zadra, 2008).

1.11.2 Sleep Dimensions

It is essential to define sleep and its dimensions to gauge its effects on general health and comprehend the qualities of healthy sleep (Buysse, 2014). Buysse (2014) defines five dimensions of sleep: Sleep Duration, Sleep Continuity/Efficiency, Sleep Timing, Alertness/Sleepiness, and Sleep Satisfaction/Quality. Other potential dimensions include Sleep Restoration/Restfulness, Sleep Depth/Soundness, Regularity, and Sleep architecture. (Jones, 2005; Buysse, 2014). The details of 5 dimensions that are explained below:

- **Sleep Timing**

  Sleep timing is sometimes defined in different ways: It can refer to the time a person goes to bed, or it may refer to the midpoint of their sleep. Additionally, sleep timing

is often used to estimate circadian chronotype, which indicates whether an individual tends to prefer morning or evening activities (Buysse, 2014).

- **Sleep Efficiency**

  Sleep efficiency is an indicator of sleep quality (Buysse, 2014). It is defined as the proportion of time spent asleep while in bed. Sleep efficiency consistently measures sleep continuity and provides valuable insight into overall sleep quality (Cacioppo *et al.*, 2002).

- **Alertness**

  Alertness reflects wakefulness and sleepiness during waking hours (Buysse, 2014). Karolinska Sleepiness Scale (KSS) measure daytime sleepiness and alertness levels at different times of the day (Akerstedt and Gillberg, 1990; Kaida *et al.*, 2006). Another tool to measure alertness is the Epworth sleepiness scale, which focuses on the possibility of dozing off during daily life activities such as watching TV, sitting, and reading (Johns, 1991).

- **Sleep Duration**

  Sleep duration is the time between sleep onset and offset (Buysse, 2014; Ravyts *et al.*, 2021). To measure sleep duration, both objective and subjective tools are commonly employed. Although there are correlations between these approaches, discrepancies often arise: Self-reported sleep duration tends to be overestimated compared to objective assessments, such as actigraphy or polysomnography (Silva and Walsleben, 2007).

- **Sleep Satisfaction/Quality**

  Sleep satisfaction, or how individuals perceive the quality of their sleep, is the subjective assessment of "good" and "poor" sleep (Buysse, 2014). Tiredness on awakening and sleep fragmentation are the most important factors relating to sleep quality (Buysse, 2014; Dickerson, Klingman and Jungquist, 2016). Self-report questionnaires and sleep diaries are widely used tools to assess sleep quality by capturing different dimensions of the sleep experience. The most commonly used questionnaire is The Pittsburgh Sleep Quality Index (PSQI), which is a 19-item questionnaire that assesses seven key areas: sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleeping medication, and daytime dysfunction (Buysse *et al.*, 1989). It is particularly effective in identifying individuals with poor sleep quality or potential sleep disorders (Buysse *et al.*, 2008). Whereas, sleep diaries provide a more personal and immediate

measure of sleep quality by allowing participants to rate their nightly sleep satisfaction using Likert or visual analogue scales (Krystal and Edinger, 2008).

- **Sleep Restoration/Restfulness**

  Sleep Restoration/Restfulness is a subjective measure typically evaluated in terms of "non-restorative sleep," which means sleep that does not leave a person feeling refreshed. This is also related to sleep quality. However, its specific links to health outcomes are not well-defined. (Buysse, 2014).

- **Sleep Depth/Soundness**

  Sleep Depth/Soundness is linked to physiological measures like SWS and EEG delta activity. This dimension is associated with brain development, metabolic function, and pain perception. However, it lacks an equivalent of a direct self-report (Buysse, 2014).

- **Regularity**

  Regularity refers to the consistency of an individual's sleep and wake times (Buysse, 2014).

- **Sleep Architecture**

  Sleep architecture refers to the organisation of different sleep stages during a normal sleep cycle and requires advanced techniques, such as polysomnography, for measurement (Jones, 2005). Sleep debt or soundness could also be considered as part of this definition.

Each dimension is linked to specific health outcomes and can be framed positively, with optimal states for each. However, not all dimensions are unidirectional. For example, sleep duration and timing are healthy only within specific ranges and deviations from these ranges cause adverse effects. These sleep dimensions can be measured through various methods, such as self-reports (questionnaires, sleep diaries), behavioural measures (actigraphy), and physiological measures (polysomnography). Sleep satisfaction/quality lacks a direct physiological measure, but it may correlate with some physiological variables such as slow-wave sleep (SWS) and delta-wave activity in EEG (Buysse, 2014). However, a recent study found that self-reported sleep quality was significantly better with fewer awakenings and longer REM sleep but was not significantly associated with SWS (Della Monica *et al.*, 2018).

1.11.3 Navigating the Complexity of Multi-Dimensional Sleep Assessment

Despite its importance, sleep terminology can be confusing, making comparisons between studies difficult. Although sleep dimensions are defined (Buysse, 2014), complexities still arise from using overlapping terms and varied definitions for different aspects of sleep. For example, sleep restriction and deprivation are often discussed under the dimension of sleep duration, whereas sleep disturbances can be linked to sleep quality and continuity. While sometimes treated as a standalone measure, sleep efficiency can also be grouped under sleep continuity (Kline, 2013a, 2013b; Mezick, 2013; Buysse, 2014). The details of commonly measured dimensions and related sleep terms are listed below:

- **Sleep Duration** Two of the most assessed variables of sleep duration are "time in bed" (TIB) and "total sleep time" (TST). TIB is defined as the total hours between going to bed at night and waking up in the morning. On the other hand, TST is calculated as TIB minus the time taken to fall asleep ("sleep latency" or SOL) and the time spent awake during the night ("wakefulness after sleep onset" or WASO) (Kline, 2013a).
- **Sleep restriction** refers to the partial loss of sleep, typically seen in experimental manipulations where individuals are kept awake for a portion of their usual sleep period. It also occurs naturally, such as when new parents wake repeatedly for their newborn or when an individual purposefully reduces their sleep to meet obligations. Notably, sleep restriction differs from insomnia in that restricted individuals lack the opportunity to sleep, whereas those with insomnia struggle to sleep despite having the opportunity (Kline, 2013a).
- **Sleep deprivation** is characterised by total sleep loss, which is often studied in experimental settings. However, it can also occur in naturalistic situations, such as a student staying awake all night to study (Kline, 2013a).
- **Sleep Continuity** refers to the ability to maintain sleep. Related terms include sleep latency, efficiency, and wake after sleep onset (WASO) and fragmentation index. **Sleep latency** measures the time it takes to fall asleep after going to bed, while **WASO** measures the total time awake during the night. **Sleep efficiency (SE)** is a proportional measure of continuity, which is represented as the percentage of time spent asleep in bed (Mezick, 2013). Fragmentation index derived from dividing the

total number of awakenings and sleep stage shifts by the total sleep time in hours ('A Preliminary Report from the Sleep Disorders Atlas Task Force of the American Sleep Disorders Association', 1992)

- **Sleep Quality** is a key construct for clinicians and researchers due to its relevance to optimal health and functioning. However, there is no universally accepted aspects of sleep quality (Krystal and Edinger, 2008). It is due to the subjective nature of meaning of "quality". For example, individuals may define their sleep quality differently: one person may prioritise ease of falling asleep, while another may focus on minimising awakenings throughout the night (Krystal and Edinger, 2008). This subjective nature makes sleep quality challenging to define and measure, as it can include aspects like wakefulness after sleep onset, sleep disturbance and feelings of refreshment upon waking (Harvey *et al.*, 2008). Therefore, Sleep quality is sometimes measured through objective measures such as sleep onset latency, WASO, sleep efficiency, or the number of awakenings. In addition, polysomnography may be used to assess sleep depth: increased N1 (superficial sleep) is often associated with poor sleep quality and increased N3 (deep sleep) is linked to good sleep quality. Despite correlations, sleep quality is not synonymous with these objective variables. This kind of correlation is not established with sleep duration; short and long sleep durations can be associated with poor sleep quality (Kline, 2013b; Della Monica *et al.*, 2018). Having said that, many aspects of sleep quality cannot be measured objectively. Therefore subjective methods such as sleep diaries or questionnaires are commonly used to measure sleep quality (Kline, 2013b).

These domains collectively form the concept of sleep health. However, most studies operationalise only one or a subset of these domains (Buysse, 2014). Employing several measures together can provide a fuller picture of sleep health compared to focusing on a single dimension (Koinis-Mitchell *et al.*, 2015). To bridge this gap, a comprehensive sleep assessment was conducted in this study to examine its relationship with motor function after stroke. Sleep quality was measured through direct questioning via sleep diaries and questionnaires. Additionally, other dimensions—sleep duration and continuity—were also assessed using both objective and subjective methods.

1.12 Limitations and Challenges in Measuring Motor Function after Stroke

Kinematic analysis is an effective method for evaluating motor function because it enables differentiation between true recovery and compensatory strategies (Bernhardt *et al.*, 2017). This distinction is essential, as research has shown that many perceived improvements in outcomes may stem from compensatory mechanisms rather than true recovery. For instance, stroke patients often regain balance not by enhancing muscle activation in the paretic limb but by increasing activity in the non-paretic side (Garland *et al.*, 2003). Moreover, balance improvements can occur without the normalisation of weight distribution in the paretic leg (De Haart *et al.*, 2004; Roerdink *et al.*, 2006), Similarly, when standing on a moving platform, individuals frequently shift their centre of mass towards the non-paretic leg (Vanasseldonk *et al.*, 2006). Therefore, kinematic analysis is needed to examine movement pattens and understand motor function (G. Kwakkel *et al.*, 2019).

Furthermore, a recent roundtable highlighted that the FMA-LE lacks responsiveness, exhibits ceiling effects, and is influenced by muscle strength demands. However, there is currently no psychometrically superior alternative for evaluating pathological synergistic movements in the lower extremities after stroke. This gap may be addressed by incorporating kinematic and kinetic measures to assess movement quality (Van Criekinge *et al.*, 2024). These measures are considered among the most objective and detailed methods for tracking recovery progress after stroke (Mensen *et al.*, 2019). However, despite their effectiveness, kinematic assessments have not yet been used in research on sleep and recovery after stroke. This represents an opportunity to improve understanding of the role of sleep in motor function by integrating objective movement analysis. This method was utilised in this current study to address the gap.

Lower limb recovery plays a significant role in regaining mobility and independence. However, studies on sit-to-walk (STW) biomechanics remain scarce, particularly among older adults or those with impaired STW movements. There is a pressing need for further research into STW techniques and the fluency of transitions to understand better and enhance recovery outcomes for these populations (Perera *et al.*, 2022). To improve understanding in this area and in line with the recommendation to use kinematic measurements, fluency metrics of STW movement have been selected as biomechanical

assessment variables of motor function after stroke. This approach aims to provide a more precise analysis of movement quality and the recovery process.

Moreover, normative data is needed for new assessments like fluency assessments that reflect the performance of neurologically healthy individuals. This data is crucial for accurately evaluating motor function through kinematic analysis, as it allows for meaningful comparisons between stroke patients and healthy controls (G. Kwakkel *et al.*, 2019; Kwakkel *et al.*, 2023). To ensure the validity and consistency of these assessments, it is essential to establish the reliability of fluency metrics. Therefore, in this project, the test-retest reliability of fluency metrics has been addressed through a dedicated study.

1.13 Research Objectives

The literature reveals several gaps in understanding the role of sleep in post-stroke recovery. Although studies indicate that sleep disturbances may negatively affect recovery outcomes (Fulk *et al.*, 2020), the literature lacks a clear delineation of sleep-related terms and dimensions. Moreover, many studies implemented measurement of one sleep dimension (Buysse, 2014; Koinis-Mitchell *et al.*, 2015). In response, this study adopted a holistic approach to assessing sleep health by evaluating multiple dimensions which are quality, duration and continuity. Beyond sleep's role in physical health, sleep is closely tied to mental health outcomes (Scott et al., 2021). Given this strong relationship, in this project, mental health assessments are incorporated to understand the interplay between sleep and motor function.

Concerning the measurement of motor function after stroke, many investigations lack biomechanical data, an objective approach crucial for tracking true recovery without compensation (Mensen *et al.*, 2019). The recent stroke roundtable suggests that the Fugl-Meyer Assessment for Lower Extremities (FMA-LE) faces limitations such as ceiling effects and reliance on muscle strength, which underscores the need for better measures. It is recommended that this gap be addressed with kinematic and kinetic data to assess movement quality more precisely (Van Criekinge *et al.*, 2024). Therefore, this project have used biomechanical data in addition to the Fugl-Meyer assessment to investigate the link between sleep health and motor function in post-stroke populations. This has been the first

study to use biomechanical measurement to investigate the relationship between motor function after stroke and sleep.

This integrated methodology is aimed to bridge existing research gaps and provide a more comprehensive understanding of research questions, which are listed below:

Research Question 1: *What is the relationship between sleep quality and duration with motor function post-stroke?*

- **Objective 1.1:** Conduct a systematic review to identify existing evidence linking sleep quality and duration and motor function.
- **Objective 1.2:** Identify gaps in the literature.

Research Question 2: *What is the test-retest reliability of biomechanical measures of movement fluency (hesitation, coordination, and smoothness) in the non-stroke group?*

- **Objective 2.1:** Evaluate the test-retest reliability of fluency metrics.
- **Objective 2.2:** Assess the smallest detectable change (SDC) in these fluency metrics.
- **Objective 2.3:** Compare STW fluency metrics between stroke and non-stroke participants to understand motor function.

Research Question 3: *How are sleep dimensions, measured by objective and subjective tools, associated with motor function, considering confounding factors -age, gender and mental health?*

- **Objective 3.1:** Understand differences between variables derived from objective and subjective sleep measurements.
- **Objective 3.2:** To investigate the correlation between sleep and motor function-measured by kinematic analysis and Fugl-Meyer at two-time points.
- **Objective 3.3:** To investigate the relationships between motor function outcomes and the most correlated sleep measures using a robust multivariate regression model, with adjustments for demographic and psychological factors.

The structure of the thesis is designed to address these research questions systematically:

Chapter 2 presents the systematic review's findings, addressing Research Question 1, which investigates the association between sleep and motor function and identifies gaps in the literature.

Chapter 3 focuses on Research Question 2 and evaluates the test-retest reliability of fluency metrics derived from STW. This chapter lays the foundation for the robust use of biomechanical measures in subsequent analyses. It compares fluency metrics in stroke and non-stroke populations to understand recovery.

Chapter 4 builds on previous chapters by addressing Research Question 3. The association between sleep dimensions and motor function was evaluated with adjustments for demographic and psychological factors.

Chapter 5 concludes the thesis by synthesising the results, discussing their implications, and proposing directions for future research.

2 Chapter 2: Study One, The Systematic Literature Review of Sleep and motor function after Stroke

2.1 Objectives of the Systematic Literature Review

The research question for this study is: What is the relationship between sleep dimensions-quality and duration with motor function? To answer this question, the objectives are to synthesise existing evidence on the relationship between these sleep dimensions and motor function and to identify areas where further research is needed to deepen understanding of this relationship. Sleep duration and quality are chosen due to their focal points informed by their substantial roles in recovery outcomes, as illustrated by the varied impacts of sleep disorders such as insomnia, sleep fragmentation, hypersomnia, and sleep apnoea. These conditions can lead to decreased total sleep time, increased sleep fragmentation, and reduced slow-wave sleep, that effects sleep quality which is also found to compromise cognitive and physical recovery capabilities and diminish the quality of life (Wallace, Ramos and Rundek, 2012; Frohnhofen *et al.*, 2013; Ramos, Seixas and Dib, 2015; Zhang *et al.*, 2022).

Previous reviews have investigated both the macro and microstructures of sleep and its two-way relationship with stroke. These comprehensive reviews have typically adopted a holistic perspective on stroke recovery, integrating cognitive, physical, emotional, and cerebral recuperation (Duss *et al.*, 2017). Alternatively, some studies have explicitly concentrated on types of strokes or distinct sleep disorders/ dimensions, thus narrowing their scope of research (Birkbak, Clark and Rod, 2014; Gottlieb *et al.*, 2019; Luo *et al.*, 2023).

This review, however, narrows its focus from stroke to motor function after stroke without limiting it to specific stroke categories. It also considers general sleep dimensions—quality and duration—over particular sleep disorders. motor function is a foundational component of physical recovery. Physical recovery is defined in terms of activity, impairment, and participation levels, as categorised by the International Classification of Functioning, Disability, and Health (ICF). This review excludes studies primarily addressing participation and daily life activities to ensure a focus on true recovery rather than compensatory mechanisms that are significantly influenced by compensatory behaviours (Bernhardt *et al.*, 2017). Moreover, this review encompasses a variety of study types to take a

comprehensive approach to better understanding the relationship between sleep and movement recovery. Therefore, observational and experimental studies are included, except those focusing solely on pharmacological interventions.

2.2 Methods

In this systematic review, the PECO (Population, Exposure, Comparator, Outcome) approach was used to investigate the link between sleep quality and duration (exposures) and movement recovery (outcome) in stroke patients (population). There is no comparator in this study.

2.2.1 Study Design and Procedure

This systematic review's methodology followed the Cochrane Collaboration's guidelines (Higgins *et al.*, 2019), with its protocol registered in the Prospero database under the number CRD42022330664. Two reviewers, Valerie Pomeroy and I, independently conducted the study selection. Following this, I primarily managed the risk of bias assessment and data extraction. If this reviewer encountered specific issues such as discrepancies in data interpretation, incomplete data, or potential biases in study design, then assistance was sought from a second reviewer (Valerie Pomeroy) for resolution. Any disagreements during the review process were addressed through discussion between the two reviewers. When a consensus could not be reached, a third reviewer, Alpar Lazar, an expert in the sleep area, was consulted. Alpar Lazar was consulted once to resolve a rating decision.

2.2.2 Eligibility Criteria for Studies

2.2.2.1 Types of Outcomes

The main aim of this study is to understand the relationship between sleep and motor function. Studies that did not investigate this relationship were excluded. Studies where sleep quality and duration can be measured objectively (e.g., actigraphy, polysomnography) and/or subjectively (e.g., sleep diaries and questionnaires) were included in this review.

Studies that measure both sleep and motor function after stroke are included. Limitations placed for these studies are that outcome measures must include motor impairments and/or functional outcomes. Studies that solely measure cognition and/or communication function and/or spatial neglect were excluded. The tests based on self-evaluation of stroke recovery were also excluded due to reduced objectivity. Studies focusing on Motor learning were also out of the scope of this review when learning is tested by an unaffected limb due to the challenge of measuring recovery by this method.

2.2.2.2 Types of studies

The inclusion and exclusion criteria are described in Table 2-1:

Table 2-1 Types of studies, inclusion and exclusion criteria

	Criteria	Details	Rationale
Inclusion Criteria	Study Types	All types of studies except single case studies, reviews, editorials, conference abstracts, and opinion papers/letters.	The primary research that provides robust evidence is included.
	Language	Studies written in English and Turkish.	The research team is limited to English and Turkish languages.
	Risk of Bias	Studies with a low risk of bias.	Ensures methodological rigour and reliability of conclusions.
Exclusion Criteria	Study Population	Animal studies are excluded.	The focus is on human studies to ensure relevance to human behaviour.
	Intervention Focus	Studies investigating drugs/medications, including Continuous Positive Airway Pressure (CPAP) Therapy, are excluded.	This review aims to explore the relationship between sleep and movement recovery without drug effects.
	Sleep Disorder Focus	Studies solely identifying sleep disorders without evaluating sleep quality and/or duration are excluded.	The primary focus is to investigate the relationship between sleep and movement recovery.

2.2.2.3 Participants Characteristics

Studies including individuals aged at least 18 years diagnosed with stroke, regardless of stroke lesion location, time since the stroke, or number of strokes, were eligible for this

review. Including a varied group of stroke participants provides a comprehensive evaluation of sleep and motor outcomes across diverse stroke groups.

Studies including individuals with any other neurological diseases other than stroke were excluded from this review. Additional neurological diseases introduce confounding variables that may alter both sleep patterns and motor function.

2.2.2.4 Types of Intervention

The interventions examined in the included studies were not the primary focus of this review. Therefore, there were no specific inclusion or exclusion criteria based on the types of interventions, except for pharmacological studies, which were excluded. However, if non-sleep interventions were applied in the groups, only the control group was considered for inclusion if it consisted of stroke patients. This exclusion was to avoid the effect of the intervention on sleep and recovery relationships.

The rationale behind excluding pharmacological studies, even those that report baseline sleep measures, is based on their methodological requirements. These studies are usually designed to evaluate the isolated effect of a drug. To ensure this, they require strict similarity between participant groups at baseline. This similarity is often achieved using tight inclusion and exclusion criteria (Use, 2000; Food and Drug Administration [FDA], 2018). In the context of sleep-related interventions, participants are usually selected based on specific sleep disorders, such as obstructive sleep apnoea (OSA), which inherently shapes the baseline sleep profile of the sample. Our aim was to explore the relationship between naturally occurring variations in sleep and motor function after stroke. Therefore, studies with highly targeted samples were not appropriate for inclusion.

2.2.3 Searching for Studies

A research librarian assisted in developing the search strategy to ensure a thorough and exact approach. The search terms included terms associated with "exercise," "walk," "recovery," "sleep," and "stroke." The search approach was customised to meet each database's distinct indexing phrases. The databases listed below were thoroughly searched for our systematic review: Medline, CINAHL, Embase, and the Cochrane Central Register of

Controlled Trials. These searches were conducted on February 12, 2021. The search strategies were tailored to each database's specific requirements and limitations:

- **Medline:** Searches were limited to articles published in English or Turkish, excluding reviews and editorials
- **Central:** No specific limitations were applied.
- **CINAHL:** Exclusions were applied to animal studies, and review articles were used to focus on human research and primary studies
- **Embase:** Searches were refined to include only articles published in English or Turkish. Exclusions were made for nonhuman studies, reviews, editorials, letters, errata, conference abstracts, chapters, short surveys, and tombstones to streamline the focus on relevant human research articles.

Please see below for an example search string used for Embase:

1. exp brain hemorrhage/
2. exp brain ischemia/
3. exp cerebrovascular accident/
4. intracranial hemorrhage*.ti,ab.
5. hemipleg*.ti,ab.
6. hemipares*.ti,ab.
7. cva.ti,ab.
8. cerebrovascular accident.ti,ab.
9. stroke.ti,ab.
10. exp sleep/
11. exp sleep disorder/
12. exp sleep deprivation/
13. insomnia*.ti,ab.
14. hypersomnia*.ti,ab.
15. Parasomnia*.ti,ab.
16. Dyssomnia*.ti,ab.
17. Circadian rhythm.ti,ab.
18. sleep*.ti,ab.
19. exp physical medicine/
20. exp neurorehabilitation/
21. exp rehabilitation medicine/
22. exp exercise/
23. recover*.ti,ab.
24. rehab*.ti,ab.
25. physiotherap*.ti,ab.
26. physical therap*.ti,ab.
27. exercise*.ti,ab.
28. walk*.ti,ab.

29. gait.ti,ab.
30. exp walking/
31. 1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9
32. 10 or 11 or 12 or 13 or 14 or 15 or 16 or 17 or 18
33. 19 or 20 or 21 or 22 or 23 or 24 or 25 or 26 or 27 or 28 or 29 or 30
34. 31 and 32 and 33
35. limit 34 to (english or turkish)
36. nonhuman/
37. 35 not 36
38. review.pt.
39. editorial.pt.
40. letter.pt.
41. erratum.pt.
42. conference abstract.pt.
43. chapter.pt.
44. short survey.pt.
45. tombstone.pt.
46. or/38-45
47. 37 not 46

Please see Appendix 1 for the full search strings.

2.2.4 Selection of Eligible Studies

The procedure for selecting eligible studies for this systematic review was meticulous. Papers found through database searches were imported into the EndNote program. Before beginning the screening procedure, duplicates were deleted with EndNote. The remaining articles were then uploaded to the Rayyan program for screening. Any remaining duplicates were removed using Rayyan's duplication resolution feature.

Two reviewers used Rayyan software to screen the titles and abstracts of all identified papers separately. During the initial screening step, the reviewers were blind to each other's decisions. Disagreements were solved by discussion end of the screening. Studies that did not match the eligibility requirements were removed at this stage.

The full texts of potentially eligible studies were then extracted and independently evaluated by the same two reviewers. Disagreements in study selection were resolved by a discussion between the two reviewers. If no consensus could be reached, a third reviewer, an expert in the research area of sleep, was consulted.

2.2.5 Risk of Bias Assessment

The term "risk of bias" refers to the potential of systematic bias in a study's planning, execution, interpretation, or analysis, which could result in biased conclusions. Assessing the possibility of bias is critical in systematic reviews to ensure the reliability of the findings (Chandler *et al.*, 2022). This evaluation used various techniques tailored to different study types to ensure a complete and robust assessment of the risk of bias. The following sections will cover the risk-of-bias tools used in randomised controlled trials (RCTs) and non-randomised research under the criteria provided in the Cochrane Handbook (Chandler *et al.*, 2022). The assessment includes the following risk-of-bias factors, as recommended in the Cochrane Handbook for RCTs, which is a standard, comprehensive, and well-disseminated approach.

Table 2-2 Risk of bias assessment items for randomised controlled trials

Types of bias related to conduct of the study (including analysis and reporting)	Risk of bias assessment items
Selection bias and confounding	Randomisation, allocation concealment, sequence generation, control for confounders in cohort studies, and case matching in case-control studies
Performance bias	fidelity to protocol, unintended interventions, or co-interventions
Attrition bias	Completeness of outcome data, intention to-treat analysis with appropriate imputations for missing data, and completeness of follow up
Detection bias	Blinding of outcome assessors, especially with subjective outcome assessments, bias in inferential statistics, valid and reliable measures
Reporting bias	Selective outcome reporting evaluation by comparing study report and (a) protocol or (b) outcomes prespecified in methods

The criteria listed in Table 2-2 are tailored explicitly to randomised controlled trials (RCTs). For example, allocation concealment and blinding are critical to preventing selection and detection biases in RCTs. However, these criteria are not directly applicable to non-randomised studies because participants in non-randomised studies are not allocated randomly, and blinding is often not feasible. Furthermore, the risk of bias in observational studies should be assessed through different considerations, including the failure to define and apply appropriate eligibility criteria, inaccurate measurement of exposure and

outcomes, poor control of confounding variables, and incomplete or insufficiently long follow-up periods (Neumann and Schünemann, 2024). Thus, while the criteria in Table 2-2 are appropriate for assessing bias in RCTs, they should be amended or replaced with different criteria for non-randomised research or observational studies.

2.2.5.1 Criteria for Choosing the Suitable Risk-of-Bias Rating Tools

Risk of bias evaluation is a critical phase in the research process as (Mueller *et al.*, 2018). There are various suggestions for selecting an instrument for assessing risk of bias. Some of them are listed as:

- **With a clinometric instrument:** Clinometric tools evaluate the risk of bias in clinical studies.
- **Selecting a tool suitable for the research design:** Some tools are more appropriate for RCTs, whereas others are better suited to observational research.
- **Adapting the method for evaluating the possibility of bias to the study question:** The method utilised to evaluate the risk of bias should be customised to the research question being addressed (Mueller *et al.*, 2018).

In addition to the recommendations above, method guides for comparative effectiveness reviews also recommend that risk of bias tools should be (Norris *et al.*, 2011):

- **Simple to use and understand**: A complex tool is more likely to be used incorrectly, which could lead to inaccurate results.
- **Valid and reliable:** The potential sources of bias in studies may vary depending on the study design employed. Therefore, a thorough assessment of bias requires a tailored approach that considers the key threats to internal validity associated with the research question being investigated by the systematic review. To this end, various tools are available for assessing bias in different study designs (Ardern *et al.*, 2022).

The most recommended and frequently used ones are listed and compared below:

- **ROBINS-I (Risk of Bias in Non-randomized Studies - of Interventions)** was created to assess the risk of bias in estimates of the efficacy of interventions in non-randomised studies. It evaluates several potential biases, including missing data, selection bias, confounding and exposure/intervention misclassification (Sterne *et al.*, 2016).
- **ROBINS-2 (RoB 2.0)** is an improved technique for estimating the risk of bias in randomised trials. It focuses on biases that could compromise internal validity of the study, such as performance, attrition, selection and deviations from planned interventions (Sterne *et al.*, 2019).
- **ROBINS-E (Risk of Bias in Non-randomized Studies - of Exposures)** is an adaptation of the ROBINS-I instrument and assesses the risk of bias in observational studies of exposures (Higgins *et al.*, 2024).
- **Downs and Black Checklist** is used to assess the quality of observational studies. It covers selection, comparability, outcome ascertainment, follow-up, intention-to-treat analysis, confounding, publication bias, and other potential sources of bias (Downs and Black, 1998).
- **Newcastle-Ottawa Scale (NOS)** is commonly used to measure risk of bias in non-randomised studies by focusing on factors such as participant selection, comparability of study groups, and adequacy of follow-up (Viswanathan *et al.*, 2012).
- **Joanna Briggs Institute (JBI)** is a checklist used to evaluate the methodological quality and risk of bias of primary research studies included in systematic reviews, covering a wide range of study designs (Munn *et al.*, 2019).
- **The Critical Appraisal Skills Programme (CASP)** is a checklist that evaluates primary research papers across various study formats for methodological quality and potential biases (Critical Appraisal Skills Programme (CASP), 2024).

The following risk of bias tools were chosen considering the different study designs included in this systematic review, which comprises both observational studies (e.g., cohort studies, case-control studies), and randomised controlled trials (RCTs).

Regarding RCTs, the Cochrane RoB 2.0 tool was chosen due to extensive and verified domain-based approach to evaluating bias in randomised trials. It encompasses selection bias, attrition bias, and performance bias, has earned it a widespread endorsement (Sterne

et al., 2019). For observational studies: The Joanna Briggs Institute (JBI) methodological checklist was selected for observational studies due to its coverage of various study designs and its ease of use. The JBI tool includes assessments of selection bias, measurement bias, and confounding factors (Munn *et al.*, 2019).

ROBINS-I and ROBINS-E were not chosen due to their complexity and the extensive training required to apply them correctly, which could lead to inconsistency in the assessment process. While the Downs and Black checklist is comprehensive, its complexity and the extensive time commitment required may hinder its practical applicability in systematic review. The Newcastle-Ottawa Scale (NOS) is easier to use but was not selected because the JBI checklist offers a more comprehensive and transparent process that is better suited to the diverse study designs expected in this review.

2.2.5.2 Risk of Bias Assessment Process

Assessing the risk of bias in this systematic review involved several steps to ensure accuracy and consistency:

- **Initial Assessment:** One reviewer independently assessed the risk of bias for each included study using the appropriate tool.
- **Verification:** When the primary reviewer was uncertain about a study's inclusion based on the risk of bias, they consulted a second reviewer.
- **Resolution of Discrepancies:** Any disagreements between the two reviewers were resolved through discussion. If consensus could not be reached, a third reviewer was consulted.
- **Threshold for Inclusion:** The risk of bias assessment for studies involved specific thresholds to determine their suitability for inclusion. For the JBI checklist, studies were required to achieve a 75% or higher 'yes' response rate to be considered low risk of bias. The risk of bias in RCTs is measured using the RoB 2.0 tool, which automatically categorises the level of bias (Jørgensen *et al.*, 2016; Sterne *et al.*, 2019). Therefore, RCTs identified as having a low risk of bias meet the standards established for this review.

Additionally, this process was meticulously recorded in an Excel file. Each sheet corresponds to a specific type of study. The answers to the risk of bias tool questions were marked for each study after they were listed on the sheet according to their type. Based on the criteria, studies categorised as having a low risk of bias were highlighted.

2.2.6 Outcomes

Motor function is the primary outcome of this systematic review. However, sleep duration and quality are essential secondary outcomes given the nature of the research subject, which investigates at the connection between sleep and motor function. These sleep dimensions were evaluated using both objective and subjective methods.

2.2.6.1 Outcome Measurements

A variety of assessment tools were used to evaluate the outcomes of interest. This section details and categorises the instruments employed to measure movement recovery and sleep for comprehensive analysis.

2.2.6.1.1 Movement Recovery Assessment Tools

This review aligned the classification of motor function tools with the ICF framework. From the studies included, six assessment tools were identified for evaluating motor function, grouped into measures of motor impairment and measures of activity. This classification is important because it distinguishes between impairment and activity. Impairment refers to problems in body function and structure, while activity involves performing tasks or actions.

Table 2-3 shows the specific ICF domains that each assessment tool addresses. If an assessment tool encompassed activity and impairment outcomes, it was categorised based on its predominant content. It was determined by evaluating which aspect constituted the majority of the tool's items or which aspect was the primary focus of the tool's overall application and usage in the study.

Table 2-3 ICF domains of motor function assessment batteries

ICF domains		6-MWT	K-BBS	WMFT	MAS	BRS	FMA
Body Functions and structures	Neuromuscular and movement related functions				X	X	X
Activities	Mobility	X	X	X			X

BRS (Brunnstrom Recovery Stages), MAS (modified Ashworth scale), FMA (Fugl-Meyer Assessment), K-BBS (Korean version of Berg Balance Scale), WMFT (Wolf Motor Function Test), 6-MWT (6-minute walking test)

Brunnstrom's Recovery Stage (BRS) is a tool for evaluating motor abilities after stroke recovery (Brunnstrom, 1966). The transition from reflexive to voluntary motor control is highlighted in the six stages that progress from no movement to normal movement (Naghdi *et al.*, 2010). This method emphasises the development of spasticity and synergic movement patterns, which are directly relevant to assessing impairments in bodily functions and structures as defined by the ICF framework. Therefore, the Brunnstrom Approach is classified as an impairment scale.

The Fugl-Meyer Assessment (FMA) is a performance-based index to assess impairment levels (Fugl-Meyer *et al.*, 1975; Gladstone, Danells and Black, 2002). While it includes sections on coordination/speed, which might suggest activity-based assessments, its core focus is on impairment. The coordination/speed section includes evaluations of tremor and dysmetria (impairment measures) alongside speed (an activity measure). However, speed's contribution to the overall score is minimal, accounting for just 2 out of 66 points for upper limb assessments and 2 out of 34 for lower limb assessments. For this reason, the FMA is classified as an impairment scale (Gladstone, Danells and Black, 2002). On the other hand, The Wolf Motor Function Test (WMFT) is considered an activity scale. It measures changes in functional activities by focusing on upper extremity motor function through a series of timed tasks (Longhi *et al.*, 2016). Therefore, motor function assessment batteries measure impairments as follows:

- BMR (Brunnstrom motor recovery) Stage
- MAS (modified Ashworth scale)
- FMA (Fugl-Meyer Assessment)

The assessment batteries measure activities are:

- K-BBS (Korean version of Berg Balance Scale)

- WMFT (Wolf Motor Function Test)
- 6-MWT (6-minute walking test)

2.2.6.1.2 Sleep Assessment Tools

Sleep assessment tools are categorised into two groups: one measuring sleep quality and the other measuring sleep duration. Although The Pittsburgh Sleep Quality Index (PSQI) is a sleep quality questionnaire, it includes a specific question for sleep duration.

Sleep Quality Assessments:

- Pittsburgh Sleep Quality Index (PSQI)
- Sleep Quality Scale (SQS)
- Epworth Sleepiness Scale (ESS)
- Insomnia Severity Index (ISI)
- Stanford Sleepiness Scale (SSS)

Sleep Duration Assessments:

- Actigraphy
- Sleep diary

2.2.7 Data Extraction Process

Data were extracted from the included studies focusing on specific characteristics and measurements relevant to this systematic review. The data extraction process included the following elements:

- **Participant Characteristics:** Information on the number of patients, age, gender, type and affected side of stroke, time elapsed since the stroke occurrence, and stroke severity.
- **Measurement Data:** Data about interested outcomes, sleep and motor function evaluation methods, and follow-up times.
- **Control Condition Details:** If a study uses sleep intervention, intervention details, such as the circumstances of the control group, are recorded.

The first reviewer extracted the data, and then a second reviewer reviewed it for its accuracy and completeness. Reviewer disagreements were settled in a meeting where issues were explored, and the final decision was made. In studies involving an intervention, only the baseline data was extracted for both stroke and control participants to exclude any influence of the intervention on motor function. If any data from included studies needed to be included or clarified, the authors of the study reports were contacted via email to request the relevant information.

2.2.8 Data Synthesis

This systematic review investigated the relationship between sleep parameters and motor outcomes after stroke. Substantial methodological heterogeneity was identified among the studies, covering diverse interventions, outcomes, and designs, which rendered meta-analysis unfeasible. Therefore, narrative synthesis was chosen to analyse the background, methods, and findings of the investigation and provide a qualitative summary of the results (Popay *et al.*, 2006). Despite concerns about analytical validity in such contexts (Ioannidis, Patsopoulos and Rothstein, 2008) and challenges in synthesis methods (Valentine, Pigott and Rothstein, 2010), a systematic review has been chosen based on the guidance provided by Munn *et al.* (2019). Munn *et al.* (2019) indicate that a systematic review is preferable when the objective is to address a focused question with potential implications for practice or policy. Thus, the systematic review method is aligned with the intent to provide a robust and critical synthesis of the evidence on sleep and stroke, even without meta-analytic feasibility.

In this review, included studies have used various measurement batteries, making direct comparisons challenging. To enable comparison in those studies and generate the scatter plot with the data, their scores were normalised by dividing both the mean and standard deviation by the range of each respective measurement scale. For instance, with a dataset adjusted to a scale of 1-6: Scale: 1-6, Mean: 0.71, Standard Deviation: 0.576. The correct approach to normalisation considers the range of possible scores, which is 5 (6 - 1), rather than just the maximum score: Normalised Mean: (0.71 - 1) / 5 = -0.058; Normalised Standard Deviation: 0.576 / 5 = 0.1152

2.3 Results

2.3.1 Identification of Included Studies

A total of 2,413 records were identified across multiple databases, including CINAHL (472), Embase (1,093), Medline (562), and registers such as CENTRAL (286). After removing 693 duplicates, the remaining records were screened for eligibility. After screening 1,720 records, 1,480 were excluded, leaving 240 reports for eligibility assessment. Out of the 240 reports identified and assessed for eligibility, 229 were excluded for the following reasons: 137 reports had unsuitable outcome measures, 39 were of an inappropriate study design, 6 were study protocols that had not yet been completed, 12 did not examine the relationship between sleep and stroke outcomes. 35 were focused on drug or pharmacological interventions, of which 33 investigated CPAP therapy for OSA and the remaining 2 involved sleep-related pharmacological agents. In all of these, the sleep problem was a prerequisite for inclusion, making the baseline sleep data highly condition-specific rather than representative of broader post-stroke populations.

Following these exclusions, 11 studies met the inclusion criteria. A Risk of Bias assessment was conducted on these 11 studies, revealing that 7 had a low risk of bias, as detailed in the following section. Consequently, these seven studies were included in the final assessment. The process is summarised in the PRISMA 2020 flow diagram (Figure 2-1).

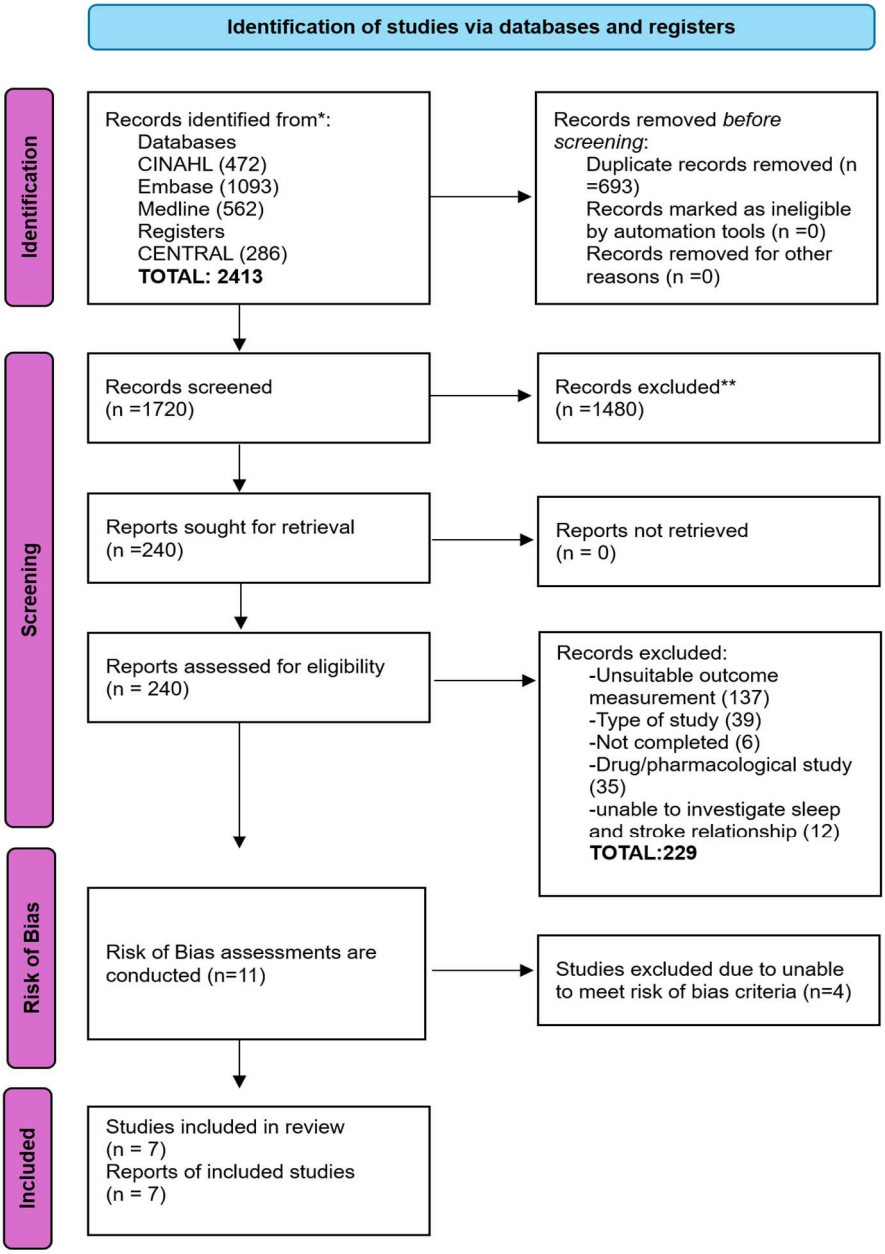


Figure 2-1 PRISMA 2020 flow diagram, From: Page 5, MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71

2.3.2 Risk of Bias Assessment

The risk of bias assessment was conducted for eleven studies that met the eligibility criteria for this review according to their study types. After carefully evaluating eleven studies, seven were accepted (Joa *et al.*, 2017; Yeh *et al.*, 2017; Ye *et al.*, 2018; Davis *et al.*, 2019; Sonmez and Karasel, 2019; Kim *et al.*, 2020; Silva *et al.*, 2021); four were rejected (Lubart *et al.*, 2017; Gezer *et al.*, 2019; Fulk, Duncan and Klingman, 2020; Pereira *et al.*, 2020).

The cross-sectional studies included in this evaluation differ significantly in methodological quality measured by the JBI Critical Appraisal Checklist for analytical cross-sectional studies. As Table 2-4 illustrates, four of the seven studies considered fulfilled the inclusion criteria, indicating that a significant number did not. Typical flaws include inadequate strategies to identify and manage confounders (Items 5 and 6).

Table 2-4 Quality of evidence for cross-sectional studies (n = 7)

Study	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8
(Gezer *et al.*, 2019)	YES	YES	YES	YES	NO	NO	YES	YES
(Davis *et al.*, 2019)	YES	YES	YES	YES	YES	YES	YES	YES
(Silva *et al.*, 2021)	YES	YES	YES	YES	YES	YES	YES	YES
(Kim *et al.*, 2020)	YES	YES	YES	YES	YES	YES	YES	YES
(Sonmez and Karasel, 2019)	YES	YES	YES	YES	YES	YES	YES	YES
(Fulk, Duncan and Klingman, 2020)	YES	YES	YES	NO	YES	NO	YES	YES
(Pereira *et al.*, 2020)	YES	YES	YES	YES	NO	NO	YES	YES

Item 1: Were the criteria for inclusion in the sample clearly defined?
Item 2: Were the study subjects and the setting described in detail?
Item 3: Was the exposure measured in a valid and reliable way?
Item 4: Were objective, standard criteria used for measurement of the condition?
Item 5: Were confounding factors identified?
Item 6: Were strategies to deal with confounding factors stated?
Item 7: Were the outcomes measured in a valid and reliable way?
Item 8: Was appropriate statistical analysis used?

The As detailed in Table 2-5, the two cohort studies met all inclusion criteria. However, items 6 and 9 of the JBI Critical Appraisal Checklist for cohort studies are uncertain, specifically whether participants were free of the outcome at the start and the completeness of follow-up.

Table 2-5 Quality of evidence for cohort studies (n = 2)

Study	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Item 11
(Joa *et al.*, 2017)	YES	YES	YES	YES	YES	YES	YES	YES	UNC	UNC	YES
(Yeh *et al.*, 2017)	YES	YES	YES	YES	YES	UNC	YES	YES	YES	N/A	YES

UNC: Unclear, N/A: Not Applicable
Item 1: Were the two groups similar and recruited from the same population?
Item 2: Were the exposures measured similarly to assign people to both exposed and unexposed groups?
Item 3: Was the exposure measured in a valid and reliable way?
Item 4: Were confounding factors identified?
Item 5: Were strategies to deal with confounding factors stated?
Item 6: Were the groups/participants free of the outcome at the start of the study (or at the moment of exposure)?
Item 7: Were the outcomes measured in a valid and reliable way?
Item 8: Was the follow-up time reported and sufficient to be long enough for outcomes to occur?
Item 9: Was follow-up complete, and if not, were the reasons for loss to follow-up described and explored?
Item 10: Were strategies to address incomplete follow-up utilized?
Item 11: Was appropriate statistical analysis used?

The reviewed randomised controlled trials (RCTs) demonstrate varied quality (Table 2-6). One of the two studies considered was included. Specific methodological concerns involved problems with randomisation, outcome measurement, and the selection of reported results assessed by a revised tool to assess the risk of bias in randomised trials (RoB 2).

Table 2-6 Quality of evidence for RCTs (n = 2)

Study ID	D1	D2	D3	D4	D5	Overall
(Ye *et al.*, 2018)	+	+	+	+	+	Low risk
(Lubart *et al.*, 2017)	-	+	+	-	-	High risk

D1: Randomisation process
D2: Deviations from the intended interventions
D3: Missing outcome data
D4: Measurement of the outcome
D5: Selection of the reported result

2.3.3 Characteristics of Included Studies

The total number of included studies is seven. They encompass a range of countries and study designs. Studies were conducted in South Korea (n=2, (Joa *et al.*, 2017; Kim *et al.*, 2020)), Canada (n=1, (Davis *et al.*, 2019), Turkey (n=1,(Sonmez and Karasel, 2019)), Brazil (n=1, (Silva *et al.*, 2021)), China (n=1, (Ye *et al.*, 2018)), and Taiwan (n=1, (Yeh *et al.*, 2017)).

These studies were mainly cross-sectional (n=4, (Davis *et al.*, 2019; Sonmez and Karasel, 2019; Kim *et al.*, 2020; Silva *et al.*, 2021)). Other study types are cohort study (n=2, (Joa *et al.*, 2017; Yeh *et al.*, 2017)) and one randomised controlled trial (n=1, Ye *et al.*, 2018)).

The characteristics of these studies are diverse (Table 2-7). Sample sizes varied from 20 to 208 participants; the mean age of participants ranged from 48.17 to 69.0 years, with a mix of male and female participants. The time post-stroke participants were assessed ranged from 12.1 days to over seven years, covering both acute and chronic phases.

Various assessment tools are used to measure sleep and motor function (Table 2-7). Sleep quality was predominantly measured using the Pittsburgh Sleep Quality Index (PSQI) (Yeh *et al.*, 2017; Ye *et al.*, 2018; Davis *et al.*, 2019; Sonmez and Karasel, 2019; Silva *et al.*, 2021), with some studies employing additional measures like the Insomnia Severity Index (ISI) and the Epworth Sleepiness Scale (ESS) (Kim *et al.*, 2020).

Stroke outcomes were assessed using various impairment and activity assessment tools, mostly Fugl-Meyer assessment (FMA) (Ye *et al.*, 2018), Six-Minute Walk Test (6-MWT) (Davis *et al.*, 2019; Silva *et al.*, 2021), and the Korean version of the Berg Balance Scale (K-BBS) (Kim *et al.*, 2020; Joa *et al.*, 2017) (Table 2-7).

In some studies, participants were divided into multiple subgroups based on baseline sleep quality (Sonmez and Karasel, 2019; Yeh *et al.*, 2017) and insomnia status (Kim *et al.*, 2020) using PSQI and K-ISI questionnaires. Stroke recovery outcomes are then compared between these subgroups to explore any potential differences in recovery trajectories (Table 2-7).

Table 2-7 Characteristic of included studies

	Authors, year	Country	Study Design	N	Subgroups	type of stroke & stroke severity	Sex (Female: Male)	Mean age (SD)	Time after Stroke	Sleep Measure	Motor Function measure
1	(Davis *et al.*, 2019)	Canada	cross-sectional observational design	72	.	ischemic or haemorrhagic stroke	.	68.4 (7.6)	at least 1 year (eligibility criteria)	PSQI	6MWT
2	(Silva *et al.*, 2021)	Brazil	cross-sectional observational design	90	.	IS: %80 haemorrhagic: %20	35:55	61(12)	58.2 (58.7) months	PSQI	6MWT
3	(Kim *et al.*, 2020)	South Korea	cross-sectional observational design	112	insomnia group<15 in K- ISI (%35.7) and non-insomnia group>15 (%64.7)	mild to moderate IS: %85.5, haemorrhage: %14.5	51:61	66.23 (13.9)	an average of 20 days (assessments time)	PSQI, K-ISI, ESS, actigraphy	K-BBS,
4	(Sonmez and Karasel, 2019)	Turkey	cross-sectional observational design	50	good sleepers <5 in PSQI (%36); Poor sleepers >5 (%64)	Ischemic: %82, haemorrhage: % 18	Poor S.=22:28 Good S.=8:10	Poor S.=71(9); Good S.=68(9)	Poor S.=6.3(7.6); Good S.=9.2(7.4) years (baseline)	PSQI	MAS, BRS
5	(Ye *et al.*, 2018)	China	Randomised controlled Trial	24	.	24 with moderate OSA / IS: 21 haemorrhages: 3	7:17	65.5 (10.4)	12.10 (3.09) Days(baseline)	SSS, PSQI	FMA
6	(Joa *et al.*, 2017)	South Korea	Longitudinal observational Cohort Study	208	.	Mild stroke group (87), Moderate stroke group (121)	95:113	61.53(12.58)	32.49 (16.76) days	DSM-IV Insomnia criteria	K-BBS
7	(Yeh *et al.*, 2017)	Taiwan	Cohort Study	20	Good sleepers (PSQI ≤ 5) =5, bad sleepers (PSQI > 5) =15	Subacute stroke patients	10:10	48.17(10.59)	2.46(1.34) months	PSQI, actigraphy	WMFT

Abbreviations:
Six-Minute Walk Test (6MWT), Korean version of the Insomnia Severity Index (ISI), Epworth Sleepiness Scale (ESS), Korean version of the Berg Balance Scale (K-BBS), Modified Ashworth Scale (MAS), Brunnstrom Recovery Stages (BRS), Stanford Sleepiness Scale (SSS), Sleep Quality Scale (SQS), Wolf Motor Function Test (WMFT), Fugl-Meyer assessment (FMA), Pittsburgh Sleep Quality Index (PSQI), Ischemic Stroke (IS), Obstructive Sleep Apnea (OSA), Number of Participants (N), Sleepers (S.)

2.3.4 Narrative Analysis

2.3.4.1 Sleep Quality and Motor Function

Seven studies were included in the synthesis, each utilising a variety of measures to explore the relationship between sleep and motor function. The details are presented in Table 2-8.

Table 2-8 Assessment batteries of included studies

		Activity Measurements			**Impairment Measurements**		
		6MWT	K-BBS	WMFT	MAS	BRS	FMA
Sleep Assessments	PSQI	(Davis *et al.*, 2019; Silva *et al.*, 2021)	(Kim *et al.*, 2020)	(Yeh *et al.*, 2017)	(Sonmez and Karasel, 2019)	(Sonmez and Karasel, 2019)	(Ye *et al.*, 2018)
	ESS		(Kim *et al.*, 2020)				
	SSS						(Ye *et al.*, 2018)
	DSM-IV insomnia		(Joa *et al.*, 2017)				
	ISI		(Kim *et al.*, 2020)				
	Actigraphy		(Kim *et al.*, 2020)	(Yeh *et al.*, 2017)			

Six-Minute Walk Test (6MWT), Korean version of the Insomnia Severity Index (ISI), Epworth Sleepiness Scale (ESS), Korean version of the Berg Balance Scale (K-BBS), Modified Ashworth Scale (MAS), Brunnstrom Recovery Stages (BRS), Stanford Sleepiness Scale (SSS), Sleep Quality Scale (SQS), Wolf Motor Function Test (WMFT), FMA (Fugl-Meyer assessment, PSQI (Pittsburgh Sleep Quality Index

Of the seven studies included, four (Davis *et al.*, 2019; Silva *et al.*, 2021; Sonmez and Karasel, 2019; Joa *et al.*, 2017) directly examined the relationship between sleep and motor function using regression or correlation tests. The remaining three studies (Kim *et al.*, 2020; Yeh *et al.*, 2017; Ye et al., 2018) measured sleep and motor function variables without directly analysing their association; they examined the relationship by either splitting participants into two groups based on specific sleep-related factors, such as sleep duration or quality, or by evaluating participants at two different time points to observe changes in sleep patterns or behaviours over time. In these studies, the association between sleep and motor function was computed based on the reported data.

2.3.4.1.1 Motor Function Measures

Motor function assessment is done using various tools to measure different facets of impairment and activity, categorised by ICF. The range of these assessment instruments captures various aspects of recovery, such as muscular spasticity, motor function, balance, endurance, and mobility. However, this diversity also complicates comparisons between studies.

Activity Measures: motor function is assessed by activity measurements: The Six Minute Walk Test (6MWT), used by Davis et al. (2019) and Silva et al. (2021), evaluates the distance an individual can walk in six minutes. The Korean version of the Berg Balance Scale (K-BBS) is employed by Kim et al. (2020) and Joa et al. (2017) to measure balance and risk of falling. Additionally, the Wolf Motor Function Test (WMFT), utilised by Yeh et al. (2017), assesses upper extremity motor function through a series of timed tasks.

Impairment Measures: The Fugl-Meyer Assessment (FMA) is commonly used to measure motor function, as utilised by Ye et al. (2018). Muscle spasticity is measured using the Modified Ashworth Scale (MAS) employed by Sonmez and Karasel (2019). The MAS has five score points. The Brunnstrom recovery stages assess recovery in six states, from flaccidity to normal motor function. Both BRS and MAS assessment tools were applied to the upper and lower extremities separately. However, sensitivity to change in these tools is relatively low due to their broad scoring systems.

2.3.4.1.2 Correlations between Sleep Quality and motor function

The Table 2-9 summarises four studies that examined the relationship between sleep measures and motor function in stroke patients.

Table 2-9 Bivariate and multivariate association analysis between sleep quality and motor function

Authors, year	Sleep Measures	Motor Function Measures	Analysis Type	Coefficient (B, r, or R^2)
(Davis *et al.*, 2019)	Habitual Sleep Efficiency	6MWT	Multivariate Linear Regression	P= .002; R^2 = 0.13
	daytime dysfunction subsection of PSQI	6MWT	Multivariate Linear Regression	B= - 66.6 (22.4) R^2 = 0.15
(Silva *et al.*, 2021)	PSQI	6MWT	Pearson's Correlation	r= -0.25
(Sonmez and Karasel, 2019)	PSQI	BRS/upper limb	Pearson's Correlation	r=-0.43
	PSQI	BRS/lower limb	Pearson's Correlation	r=-0.40
	PSQI	BRS/hand	Pearson's Correlation	r=-0.44
(Joa *et al.*, 2017)	Difficulty Initiating Sleep (DIS):	K-BBS	Linear Regression	B (SE): -5.78 (2.83)
	Difficulty Maintaining Sleep (DMS):	K-BBS	Linear Regression	B (SE): -1.69 (2.91)
	Any Sleep Disturbance:	K-BBS	Linear Regression	B (SE): -8.75 (2.89)

Six-Minute Walk Test (6MWT), Pittsburgh Sleep Quality Index (PSQI), Brunnstrom Recovery Stages (BRS), Korean version of the Berg Balance Scale (K-BBS)

Two studies conducted a regression analysis of sleep and motor function. Davis et al. (2019) found a significant negative relationship only in daytime dysfunction of PSQI and motor function measured by 6MWT. However, it explains only 15% of the variance in motor function. In this study, habitual sleep efficiency was also associated with motor function measured by 6MWT. Other sleep quality-related components of PSQI, which are sleep disturbance, use of sleeping medication, sleep latency, and total sleep quality score, were not associated with motor function. However, Joa et al. (2017) found that in both mild and moderate stroke severity groups, individuals with sleep disturbances showed significantly less improvement in motor function, as measured by the K-BBS. This effect remained even after adjusting for depression and anxiety using linear regression. This relationship was not observed with other sleep variables.

The correlation analysis in the same study reveals that the K-BBS efficiency was found to be more related to sleep problems as it exhibited correlations with many specific sleep problems of DIS, DMS, and sleep disturbance, which are part of the Diagnostic and

Statistical Manual of Mental Disorders, Fourth Edition (DSM-IV) criteria for insomnia (Table 2-9). However, it was not significantly correlated with EMA (early morning awakening) and NRS (nonrestorative sleep). The K-BBS efficiency measures how much a patient's balance improves per day during their hospital stay. Moreover, Silva et al. (2021) discovered a negative association ($r = -0.25$, $p < 0.01$) between the PSQI total score and the 6MWT; the negative correlation coefficient indicates that physical function, as measured by the 6MWT, declines as sleep quality deteriorates. Both studies involved individuals in the chronic phase. However, this correlation has not been observed in Davis et al. (2019) study; Global PSQI was not significantly associated with physical function measured by the same assessment battery.

Sonmez and Karasel (2019) used the PSQI to assess sleep quality and the Brunnstrom Recovery Stages (BRS) to evaluate motor function. They identified statistically significant negative correlations between sleep quality and motor function across all domains, with the upper extremity ($r = -0.429$), lower extremity ($r = -0.396$), and hand function ($r = -0.444$) showing poorer motor outcomes as sleep quality worsened.

Furthermore, Sonmez and Karasel (2019) divided the participants into two groups based on their PSQI scores and compared motor function scores between poor and good sleepers. All Brunnstrom scores (upper limb, lower limb and hand) were significantly higher in the sound sleep group than in poor sleepers. However, these results were not repeated in MAS; there were no significant differences between poor and good sleepers.

2.3.4.1.3 Comparative and Longitudinal Analyses of Sleep Parameters and motor function

Table 2-10 below summarises the results from three studies examining various sleep and functional metrics that investigate relationship between sleep quality and motor function by subgroup assessments only.

Table 2-10 Comparison of sleep and motor function metrics across different groups and time frames

Study	Metric	Group-1/Time Frame-1	Mean (SD)	Group-2/Time Frame-2	Mean (SD)
(Kim *et al.*, 2020)	PSQI	Non-insomnia	10.1(2.5)	Insomnia	12.9(2.8)
	ESS	Non-insomnia	2.4(2.8)	Insomnia	4.9(5.2)
	Sleep duration	Non-insomnia	470.3 (99.1)	Insomnia	467.5 (168.1)
	K-BBS	Non-insomnia	15.1 (14.3)	Insomnia	13.7 (14.7)
(Yeh *et al.*, 2017)	PSQI	Good sleepers	3.8 (0.84)	Bad sleepers	7.53 (1.60)
	WMFT-FAS (0-5)	Good sleepers	2.61 (0.92)	Bad sleepers	2.09 (0.87)
	WMFT-TIME (0-120)	Good sleepers	11.32 (6.39)	Bad sleepers	11.49 (9.72)
(Ye et al., 2018)	FMA	1st assessment	33.3 (8.2)	2nd Assessment	42.0 (10.3)
	PSQI	1st assessment	8.0 (1.7)	2nd Assessment	7.6 (1.8)
	SSS	1st assessment	6.0 [5.0, 6.0]*	2nd Assessment	5.5 [5.0, 6.0]*

*Mean [interquartile range]
Epworth Sleepiness Scale (ESS), Korean version of the Berg Balance Scale (K-BBS), Stanford Sleepiness Scale (SSS), Pittsburgh Sleep Quality Index (PSQI), Fugl-Meyer assessment (FMA), Wolf Motor Function Test - Functional Ability Scale (WMFT-FAS), Wolf Motor Function Test – Time (WMFT-TIME)

In the first study, Kim et al. (2020) assigned participants to groups based on the presence of insomnia. The insomnia group showed lower results in motor function, as measured by the Korean version of the Berg Balance Scale (K-BBS). However, the differences were not statistically significant.

Yeh et al. (2017) utilised the PSQI to differentiate between good (PSQI score ≤ 5) and bad sleepers (PSQI score > 5). The study found that bad sleepers exhibited worse outcomes in stroke recovery, as measured by the Wolf Motor Function Test (WMFT) for time and functional ability scores. However, the statistical significance of these differences was not reported, which limits the conclusions that can be drawn.

Ye et al. (2018) uniquely measured sleep quality and motor function at two-time points within six weeks. While both sleep and motor function metrics improved over time, only the improvements in motor function, evaluated using the Fugl-Meyer Assessment (FMA), reached statistical significance ($p<0.05$). Changes in sleep quality, assessed using the Standford Sleepiness Scale (SSS) and PSQI, were not statistically significant.

It is hard to draw a conclusion based on the Table 2-10 summarising the differences in sleep quality and motor function metrics across three studies (Kim et al., 2020; Yeh et al., 2017; Ye et al., 2018). Therefore, a scatter plot (Figure 2-2) was created to visually represent the data and observe the relationships and trends between sleep quality and motor function outcomes among different groups. PSQI was considered for this plot since it was common in all three studies; motor function was measured using K-BBS, WMFT-FAS and FMA, respectively.

To allow for comparison across the studies and to generate the scatter plot, the scores were normalised. This was done by dividing both the mean and standard deviation by the range of each measurement scale. This method is known as min-max scaling. The rationale for using min-max normalisation was to enable meaningful comparisons between data obtained from different assessment tools. By bringing all scores onto a common scale ranging from 0 to 1, the data became directly comparable. As noted by Tawakuli et al. (2024), normalisation is a key preprocessing step. It helps ensure comparability across heterogeneous datasets and contributes to improved data quality. Min-max scaling is especially suitable when the minimum and maximum values of a dataset are known. It maintains the relative distribution of scores while standardising them to a fixed range. The detailed procedure used for this normalisation is provided in Section 2.2.8 (Data Synthesis) on page 66.

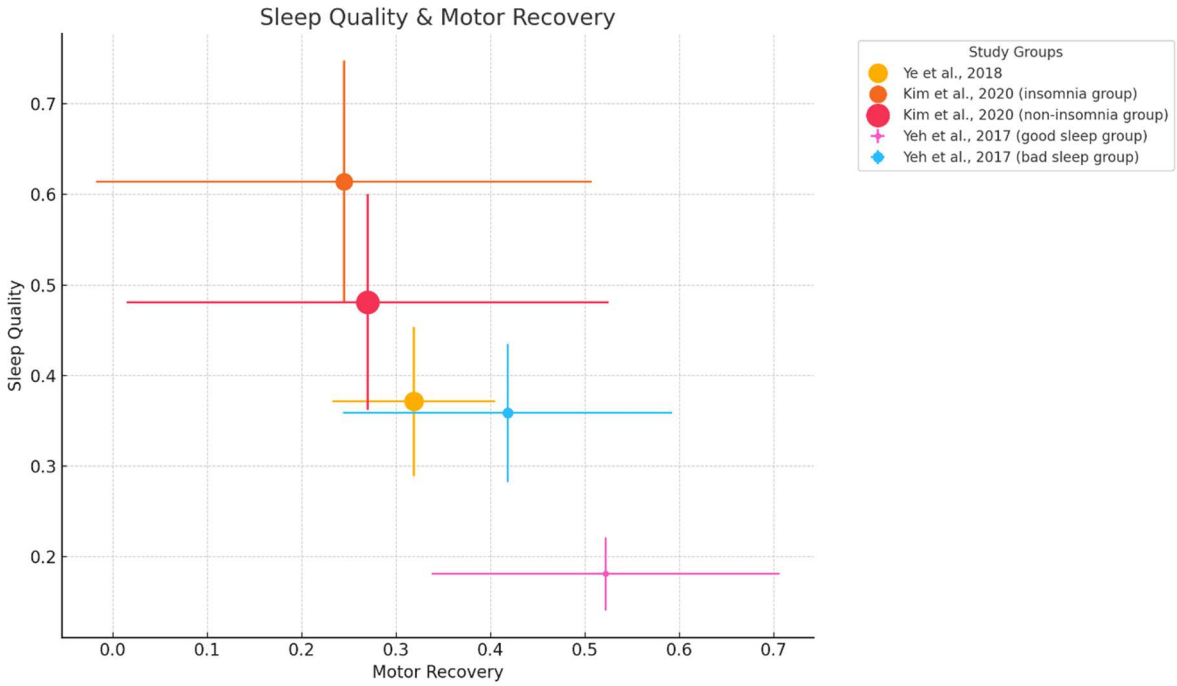


Figure 2-2 Relationship between motor function (x-axis) and sleep quality (y-axis) across studies. The mean values for each study are represented as dots, with horizontal lines indicating the standard deviation (SD) for motor function and vertical lines representing the SD for sleep quality. The size of each dot reflects the sample size of the study.

All studies measured sleep quality using the PSQI, where larger values indicate poorer sleep quality. Conversely, higher values on the motor function assessments reflect better recovery. Based on this, the overall trend in Figure 2-2 suggests that better sleep quality tends to be associated with better motor function. However, the variability in the data, along with overlapping standard deviations across the different study groups, suggests that the relationship between sleep quality and motor function is complex. These variations indicate that other factors may influence both sleep quality and motor function, making it difficult to draw definitive conclusions from this trend alone.

2.3.4.2 Sleep Duration and motor function

Only two researchers, Kim et al. (2020) and Davis et al. (2019) investigated the association between sleep duration and motor function. Davis et al. (2019) found a correlation between sleep duration, as a component of the PSQI, and motor function, measured by the 6-Minute Walk Test (6MWT). However, the results were at the threshold of statistical significance (B = 0.0014, SE = 0.0007, r^2 = 0.05, p = 0.05). Kim et al. (2020) compared groups with and without subjective insomnia but found no significant changes in sleep duration measured by

actigraphy or motor function as evaluated by the Korean version of the Berg Balance Scale (K-BBS).

2.4 Discussion

2.4.1 Challenges for Synthesis Results from the Studies

The studies in the review exhibit variability in geographic location, study design, sample size, and sleep and stroke outcome assessment methods. Therefore, making comparisons is challenging. There are also variations in how stroke severity and time after stroke are measured, with some studies focusing on early recovery (e.g., Ye et al., 2018; Joa, 2017) and others on mostly chronic stages (e.g., Davis et al., 2019; Silva et al., 2021).

Regarding sleep-related variability, some studies excluded patients with prior sleep disorders or those using psychotropic medications (e.g., Kim et al., 2020; Ye et al., 2018), while others did not impose strict exclusion criteria (e.g., Joa et al., 2017). Assessment tools for sleep also differ: Sleep is mainly measured by the Pittsburgh Sleep Quality Index (PSQI), In addition, some studies include objective assessments, such as actigraphy, or use scales like the Epworth Sleepiness Scale (ESS).

Stroke recovery measures vary considerably, with assessments covering a range of impairments and functional activities. Common tools include the Six Minute Walk Test (6MWT) for activity, the Berg Balance Scale (K-BBS) for balance, and the Fugl-Meyer Assessment (FMA) for motor function. This diversity in tools complicates direct comparisons across studies. Overall, the variability in stroke patients, sleep and stroke recovery assessment tools makes it challenging to compare studies and draw definitive conclusions about the relationship between sleep and stroke recovery.

2.4.2 Summary of Findings

2.4.2.1 Sleep Quality

The studies in this review highlight that there are correlations between sleep quality and motor function. However, not all of these correlations are significant, and their strength varies depending on patient demographics and the assessment tools used. Davis et al.

(2019) and Silva et al. (2021) demonstrate how specific aspects of sleep, such as daytime dysfunction and poor sleep quality, correlate with decreased physical performance measured by 6MWT. Similarly, Sonmez and Karasel (2019) emphasise that lower sleep quality is consistently linked with poorer motor outcomes across various domains measured by the Brunnstrom scale. Joa et al. (2017) further illustrate the detrimental effects of sleep disturbances, specifically insomnia, on balance and motor functions as assessed by the K-BBS. Other studies (Kim et al., 2020; Yeh et al., 2017; Ye et al., 2018) could not show a significant relationship between sleep and motor function. In summary, Poor sleep quality is frequently linked to poorer motor function outcomes, while the intensity and severity of these connections diverge. The variability of the studies may affect the ability to draw clear conclusions.

2.4.2.2 Sleep Duration

In this review, only two studies, Kim et al. (2020) and Davis et al. (2019), have explored the relationship between sleep duration and motor function. Davis et al. (2019) found a potential association between these two but did not reach statistical significance. On the other hand, Kim et al. (2020) examined groups with and without subjective insomnia, and these two groups showed no significant difference in sleep duration or motor function. However, the larger standard deviation in the insomnia group suggests a more diverse sleep pattern, but this aspect was not explored in detail.

2.4.3 Discussion of Findings in Context of Previous Research and Addressing Knowledge Gaps

This review stands apart by specifically addressing physical recovery after stroke and narrowing the focus to motor function. This distinction is important because many studies measure recovery using Activities of Daily Living (ADL) or rather than specific motor functions (Sandberg *et al.*, 2001; Cherkassky *et al.*, 2003; Bakken *et al.*, 2012; Harris *et al.*, 2014; Jeon *et al.*, 2017; Huang *et al.*, 2018; Yaddanapudi *et al.*, 2018; Iddagoda *et al.*, 2020). Patients might improve ADL by compensating for neurological deficits with the unaffected side while the actual motor deficit remains unchanged (Duncan *et al.*, 1992). Compensation also affects activity measurements, which are usually used as standard in

stroke assessment (Saes *et al.*, 2022), but it has a more restricted effect than daily life activities.

Existing reviews have often focused on sleep disorders or deprivation and investigated the relationship between sleep and stroke recovery from a broader perspective (Wallace, Ramos and Rundek, 2012; Duss *et al.*, 2017; Laver *et al.*, 2020; Brunetti *et al.*, 2022; Frange, Murray and Coelho, 2023). However, a meta-analysis found that pooling all sleep disorder types resulted in a negative effect on recovery (Fulk *et al.*, 2020). These results are based on the Barthel Index (BI) and modified Rankin Scale (mRS) batteries, which do not measure motor function, and they are open to compensation (Fulk *et al.*, 2020). Evidence from another review suggests that the relationship between sleep and functional outcomes after stroke is stronger in patients with stroke who also have Sleep Disorder Breathing (SDB) compared to those with Restless Legs Syndrome (RLS) or insomnia. Due to their high prevalence, sleep disturbances such as SDB and insomnia are a concerning issue in chronic stroke patients, as they substantially contribute to a decline in quality of life (Brunetti *et al.*, 2022).

Several reviews provide a comprehensive look at the relationship between sleep disturbances and stroke recovery, highlighting theoretical mechanisms and connections that influence outcomes. For instance, a narrative review focusing on sleep and stroke found that sleep-related disturbances may also have a deleterious effect during the subacute and chronic phases, affecting neuroplasticity processes (Pérez-Carbonell and Bashir, 2020). Sleep plays a critical role in memory development and brain plasticity. While total sleep time and sleep efficiency are lower in patients with poor short-term outcomes after stroke, high sleep efficiency and low amounts of wakefulness after sleep onset during the acute phase of stroke have been associated with good long-term outcomes (Pérez-Carbonell and Bashir, 2020).

Similarly, another study that examined the sleep-stroke relationship with possible mechanisms investigated sleep deprivation and sleep disorders in both animal and human studies (Duss *et al.*, 2017). According to this study, poor sleep is associated with worse stroke outcomes, potentially due to mechanisms such as sympathetic activation, hypoxemia, oxidative stress, and inflammation. Sleep disorders during the subacute and chronic phases may impair neuroplasticity, attention, and cognitive performance, thereby

affecting memory consolidation (Duss *et al.*, 2017). A single review study examined sleep quality without focusing on sleep disorders, investigating only its prevalence. It found that more than half of the stroke participants had poor sleep quality but did not explore its association with recovery (Luo *et al.*, 2023).

2.4.4 Strengths and Limitations of this Systematic Literature Review

This review includes studies from various geographic locations (Canada, Brazil, South Korea, Taiwan) and study designs (cross-sectional, cohort) to expand the analysis by providing cultural and methodological viewpoints, potentially boosting the generalisability of the findings.

However, it is important to note that excluding pharmacological studies, may limit the generalisability of our findings. This decision is justified by the design of these studies, where baseline sleep characteristics are often made similar across groups to isolate the effect of the drug. This process introduces a selection bias because participants are not drawn from a general stroke population but rather from subgroups defined by specific sleep disorders. In contrast, longitudinal and observational studies usually investigate associations over time without enforcing baseline equivalence, which allows for more natural variability in sleep profiles (Van Belle et al., 2004). Therefore, while excluding drug-based studies ensures methodological alignment with our research questions, it also narrows the scope of applicability to broader clinical populations.

Another factor that may limit the generalisability of the findings is the age profile of participants across the included studies. Six out of the seven studies reported mean participant ages in the sixties, ranging from 61.0 to 71.0 years. One study, however, had a considerably younger sample, with a mean age of 48.17 years. When weighted by sample size, the overall mean age across all studies was approximately 63.8 years. The mean ages for females and males were very similar. This average is lower than the national average age at stroke, which is approximately 68 years for men and 73 years for women in the United Kingdom (Public Health England and Brine, 2018). The underrepresentation of stroke survivors aged over 70 limits how far these findings can be applied to the wider stroke population. This limitation is particularly relevant given that only around 15 percent of

strokes globally occur in individuals aged 15 to 49 years, while more than 45 percent occur in those aged 70 and above (Feigin et al., 2025).

Another limitation of this systematic review is the historic nature of the search data, which was conducted on 12.02.2021. This time lag may result in the omission of more recent studies, potentially affecting the comprehensiveness and relevance of the findings in light of emerging evidence.

The included studies represent a wide range of stroke chronicity. Time since stroke ranged from as early as twelve days in the subacute stage to several years in the chronic stage. This level of heterogeneity broadens the scope of the findings and increases their potential applicability to a diverse stroke population. However, it also reduces the precision of conclusions that can be drawn for any specific stage of stroke recovery. As a result, the generalisability of the review findings to a specific phase, such as acute or late post-stroke periods, should be interpreted with caution.

This review does not investigate the bidirectional relationship between stroke and sleep, nor does it address mental health issues, which are strongly associated with sleep quality (Baglioni *et al.*, 2016). For the sleep aspect, the review focused on two critical macro domains: duration and quality, intentionally excluding timing to narrow its scope. Instead of these, it emphasises the relationship between sleep and motor function. The dept of review might be impacted by these omissions. Rather than providing a detailed exploration of the mechanisms underlying this association, the review highlights its existence and potentially offers actionable insights for improving stroke recovery outcomes by enhancing sleep.

This review followed a methodological approach consistent with Cochrane Review guidelines. Two independent reviewers were involved in the study selection process, minimising selection bias. However, the risk of bias assessment was conducted by a single reviewer; the second reviewer was consulted only in cases of uncertainty. This approach may introduce a degree of subjectivity in evaluating study quality. However, restricting inclusion to studies with a low risk of bias enhances the overall credibility of the findings.

2.4.5 Research implications

Future research should address these gaps by incorporating large-scale, methodologically rigorous studies. These studies are also required to examine the association between sleep and motor function with multiple measurement points while controlling for chronicity and the type of stroke. This type of investigation would increase the generalisability of the results and clarify the connection between sleep and motor function. Moreover, various sleep assessments are needed to capture the multidimensional nature of sleep. To advance the field, future studies should include different dimensions of sleep, such as duration, quality, and fragmentation, while being in consensus on how to define and measure these dimensions.

3 Chapter 3: Study Two, Test-retest Reliability Study of Movement Fluency

3.1 Study Aims

Quality of movement, characterised by smoothness, coordination and hesitation, is encapsulated by the term fluency. Fluency metrics such as smoothness and hesitation have been demonstrated to distinguish between age groups, as well as healthy people and those at risk of falling(Kerr *et al.*, 2013). However, the test-retest reliability of specific fluency measurements, particularly the preferred smoothness metric, Spectral Arc Length (SPARC) (Balasubramanian *et al.*, 2015; Mohamed Refai *et al.*, 2021), and hesitation metrics in healthy people (Kerr *et al.*, 2013; Chandler *et al.*, 2021), is unknown. The STW action, which combines sit-to-stand and gait initiation, is regarded as an appropriate task for assessing movement fluency (Kerr *et al.*, 2013); nevertheless, the only fluency measurement consistently observed for sit-to-walk (STW) has been a decrease in the centre of Mass (CoM) velocity (Kerr *et al.*, 2013). Other fluency metrics, coordination and smoothness, are rarely investigated.

Establishing the reliability of fluency metrics (hesitation, coordination, and smoothness) is crucial for advancing our understanding of motor function in subsequent studies that utilise the same metrics, thereby providing a solid foundation for interpreting the outcomes and ensuring the robustness of the findings. Therefore, the objectives of this study were to evaluate the test-retest reliability of kinematic metrics of movement fluency: Hesitation, coordination, and smoothness, across two sessions. The study also sought the Coefficient of Variation (CV), Standard Error of Measurement (SEM) and smallest detectable change (SDC) in these kinematic metrics—specifically smoothness, hesitation, and coordination to determine the reliability and sensitivity of the biomechanical metrics to detect meaningful changes.

This study also aims to compare sit-to-walk (STW) fluency metrics between stroke and non-stroke participants to better understand recovery after stroke. The biomechanical data of stroke participants were collected using the same protocol as for non-stroke participants. In addition, clinical and sleep-related measurements were also collected. All stroke-related measurements are detailed in Study 3 (Chapter 4).

3.2 Methodology

This section covers the research design, ethical considerations, recruitment process, laboratory setting, equipment, data collection and statistical analysis.

3.2.1 Research Design

This study follows a repeated cross-sectional observational design, with two sessions held at least one week apart and up to one month apart. The aim was to assess test-retest reliability for biomechanics during a sit-to-walk task. By capturing data at different intervals, the study determines whether the measurements remain repeatable over time.

3.2.2 Ethical Considerations

The Ethical approval for this study was obtained from the UEA Faculty of Medicine and Health Ethics Committee on 26th November 2020 (Reference ID: 2020/21-028). The corresponding document is provided in Appendix 2.

The original protocol for this study was modified to facilitate the recruitment of additional participants and to obtain informed consent via online platforms. Appendix 3 contains the related approval letters. The modifications to the initial ethical approval were authorised on 22 March 2022. Ethical approval was obtained for a combined data collection procedure. This approval covered all three projects, including this one. All projects were conducted by the ABIRA (Acquired Brain Injury Rehabilitation Alliance) team. The same participants were involved across all projects.

Potential participants initially received detailed information about the study through email, phone calls, or face-to-face meetings. During these conversations, they were informed about their right to withdraw at any time without explanation. Inquiries from the potential participants about the study's procedures were addressed. If they agreed to participate in the study, they provided written informed consent online, by postal mail, or in person before taking part in the first session.

Before the first session, individuals were also required to complete an allergy screening form to detect any potential allergic reactions to materials such as sticky tape used in the

MoveExLab. Individuals with latex allergies could not be accommodated and were, therefore, unable to participate. The consent and allergy screening forms were kept in a locked drawer and are accessible only to the research team. Consent forms were also stored digitally on a password-protected section of the UEA secure server designated for MoveExLab.

3.2.3 Participants

This study specifically recruited participants based on the following criteria:

Inclusion Criteria:

- Individuals without any physical or neurological pathology or injury that could affect their movement.
- Aged 18 years or older.

Exclusion Criteria:

- Presence of any neurological or musculoskeletal pathologies that could influence movement patterns.
- Allergies to latex due to the materials used in the MoveExLab.

3.2.3.1 Sample Size

Sample size estimation was based on an a priori power calculation, following the methods described by Koo and Li (2016). An intra-class correlation coefficient (ICC) of 0.85 was selected as the target value, with a 95% confidence interval and a lower bound of 0.70. To ensure the confidence interval width did not exceed 0.15, a minimum of 54 participants was required. To account for potential missing or poor-quality data (estimated at 15%), the recruitment target was increased to 75 participants.

This approach aligns with recent recommendations from the COSMIN (COnsensus-based Standards for the selection of health Measurement INstruments) initiative. Mokkink et al. (2022) provided evidence-based guidance on sample size planning for reliability studies, highlighting the importance of selecting adequate sample sizes to ensure precise

estimation of statistics such as the ICC and standard error of measurement (SEM). The decision-making in this study reflected these principles.

However, after obtaining ethical permission for this revision, the recruitment number was raised to 85 individuals due to unanticipated technical challenges encountered during data collection, which were the initial inability to get a trigger signal and the low-quality data from the trials due to large gaps while tracking movements. These problems were solved in a few steps: technicians fixed the trigger signal, and two more mobile Vicon cameras were placed in front of the participants at their trunk level to increase the visibility of the trunk markers. It has also been decided that the quality of each trial after recording needs to be checked, which allows for detecting and solving any issues right away, like markers being masked by clothes or changing mobile Vicon camera positions for a better view.

3.2.4 Recruitment Process

Participants were selected from the local community through a variety of recruitment strategies. Posters were placed strategically around the Norwich Research Park and disseminated electronically via HSC and MED bulletins. The study was additionally promoted via specialised online platforms such as the ABIRA website (http://www.abira.ac.uk) and the RHITE database (https://brainhtc.org/rhite/), as well as general channels like the UEA newsletter called the Lasdun, UEA Blackboard, and social media outlets, including HSC Twitter and Facebook accounts.

The study advertisement invited healthy adults to take part in a research project. It explained that the project aimed to investigate how the brain recovers after a stroke by developing new ways to measure movement. The advertisement stated that participants would be asked to perform a simple everyday task. This involved standing up from a chair to answer a telephone. It also noted that movements would be recorded using non-invasive sensors and reflective markers placed on the skin. Data collected from healthy individuals would be used as a comparison to help researchers better understand recovery after stroke.

The advertisement specified that the study involved two sessions, each lasting around 60 minutes. These sessions would take place at the University of East Anglia's Movement and Exercise Laboratory. Volunteers needed to be free from neurological or musculoskeletal

conditions that could affect movement. They also needed to have no known latex allergies. The full text of the study advertisement is provided in Appendix 6.

In addition to the study advertisement on the listed channels, individuals who learned about the study from previous participants and contacted the research team were recruited. Moreover, participants from earlier studies who had given informed consent to be contacted for future research opportunities were recruited as well. When prospective participants expressed interest via email or phone, they were provided with an overview of the research project along with a detailed participant information sheet (Appendix 4). If they decided to participate, they were required to sign an informed consent form (Appendix 5).

Recruitment processes faced significant delays due to the COVID-19 pandemic and related lockdowns. Initially, data collection was planned for early 2020 but was postponed due to the first lockdown. The MoveEx lab was closed from 18 March to 1 September 2020. The lab reopened on 1 September 2020 under strict safety protocols. Additional training was conducted to ensure compliance with new regulations, including refresher training on software and marker placement skills due to the time elapsed since the initial preparation.

Data collection officially began on 22 October 2020, but participant enrolment was severely affected by ongoing restrictions. Lab access was limited due to health and safety protocols, which restricted lab occupancy and required extensive cleaning before and after each session. Recruitment was further interrupted during a second lockdown from 14 December 2020 to 12 March 2021. Following this closure, data collection resumed on 12 May 2021 but continued slowly, as lab access was limited to one participant per day to mitigate transmission risks. Scheduling difficulties also arose as the lab was in high demand due to other projects delayed by closures. Despite these challenges, data collection was completed on 26 August 2022.

3.2.5 Laboratory Setting *and Instrumentation*

This study was conducted in the Movement and Exercise Laboratory (MoveExLab) at the University of East Anglia. The lab was adapted to comply with COVID-19 safety measures: a

one-way system was implemented within the MoveExLab to maintain social distancing. Hand sanitising stations were placed at both the entrance and exit, and Personal Protective Equipment (PPE) was made available at the entrance.



Figure 3-1 MoveExLab -University of East Anglia

In the MoveExLab (Figure 3-1), an advanced integrated motion analysis system comprising the Vicon system and Bertec force plates was used. They were all synchronised through the Vicon Nexus software. This comprehensive setup is utilised in both Study 2 and Study 3.

- **Bertec Force Plates:** These are utilised to measure ground reaction forces.
- **Vicon Motion Analysis System:** This gold-standard system captures three-dimensional kinematic data and provides detailed information on movement mechanics to enable precise and reliable data collection.

3.2.5.1 Vicon Motion Capture System

The study utilised a Vicon Motion Capture System (Vicon MX, Oxford, UK) to analyse three-dimensional (3D) kinematics. The system comprises eight stable infrared cameras

stationed around the data collection area, further expanded by two additional portable infrared cameras purchased to enhance data quality (Figure 3-2). These extra cameras were strategically positioned three meters from the participants: one at approximately the same height as a person in a sitting position and the other at knee level. This camera setup is designed to improve the visualisation of the participant's movement, especially during transitions like leaning forward to stand up. It improves the visibility of markers located on the front side of the body, namely the clavicle, sternum, and left and right anterior superior iliac markers, which might be obscured during such movements (McClelland *et al.*, 2010). Consequently, this configuration leads to smaller gaps in capturing motion trajectories. All cameras are calibrated before any data collection using a five-marker calibration wand, ensuring the volume origin of the cameras is set correctly for precise measurements (Vicon, 2024).



Figure 3-2 Vicon cameras

The Vicon cameras may collect frames at a rate of 30 to 484 frames per second (fps) and offer resolutions ranging from 1.3 to 16 megapixels, depending on the models utilised. For this study, the cameras were set to a sampling frequency of 100 Hz to align with similar studies evaluating human motion. These cameras pick up on eight mm-diameter retro-reflective markers strategically positioned over anatomical landmarks (Vicon, 2024).

The Vicon system is synchronised in time with Bertec force plates, as described below, to measure a range of motion, mechanical moments, power at joints of interest, and motion acceleration for each body segment. This integrated setup permits simultaneous data collection from both the Vicon system and the Bertec force plates (Vicon, 2024).

3.2.5.2 Bertec Force Plates

In this study, three Bertec force plates were chosen, the OR6-7 model from AMTI (Watertown, MA, USA), to measure the entire-body forces of the sit-to-walk task. The technical aspects of these force plates:

- **Force Plate Specifications:** Each of the three Bertec force plates is 464 mm wide, 508mm long, and 82.6 mm deep. They have been securely embedded within a 10-meter walkway situated at the heart of our calibrated data collection area (Wilson, 2018).
- **Signal Processing:** To ensure seamless data acquisition, the amplified signals from the force plates were connected to the Vicon MX Giganet core processing unit, manufactured by Vicon (Oxford, UK), via a patch box.
- **Accuracy:** These force plates are renowned for their remarkable precision, boasting a stated linearity of ±0.2% and hysteresis of ±0.2%. These specifications guarantee highly accurate force measurements (Wilson, 2018).
- **Data Capture Rate:** The data was collected at a rapid rate of 1000 Hz (Wilson, 2018).

3.2.6 Data Collection

The data collection for this study occurred over two separate sessions held at the MoveExLab at the University of East Anglia. Upon completing a consent form and an allergy screening questionnaire during the first session, participants provided data in three categories: demographic information, anthropometric measurements, and biomechanical data related to sit-to-walk movements. The biomechanical data are collected using motion analysis systems, which have been introduced in the previous section. The second session followed the same protocol without repeating demographic or anthropometric

measurements. The first session took around one hour. The second session, however, was slightly shorter due to fewer measurements being taken.

Participants wore a sleeveless t-shirt and shorts during the movement analysis procedure to allow for the placement of reflective markers on anatomical landmarks. The MoveExLab provided these clothes, which were washed in compliance with COVID-19 regulations after each use. Participants changed into these garments in a designated changing area separated from the main MoveExLab area. Additionally, participants were given single-use plastic bags to store their clothing in after data collection.

- **Demographic Information:** Before the motion analysis, all essential demographic information were gathered; namely age, gender, and hand dominance.
- **Anthropometric Measurements:** Essential anthropometric measurements are conducted according to Vicon system recommendations to ensure accurate marker positioning and joint centre calculations. These included body mass, height, inter-ASIS distance, leg length, knee width, ankle width, elbow width, wrist width, hand thickness, and shoulder offset. These measurements are necessary for the Vicon motion analysis system to accurately determine body segments and calculate joint centres (Vicon, 2024).
- **Biomechanical measurements:** Before biomechanical measurements, participants were prepared by attaching reflective markers to their skin according to Vicon's guidelines, as illustrated in Figure 3-3 and Figure 3-4 (Vicon, 2024). Markers highlighted with an orange line in the figures were not applied because they are specific to the use of a Knee Alignment Device, which was not applicable in this study.

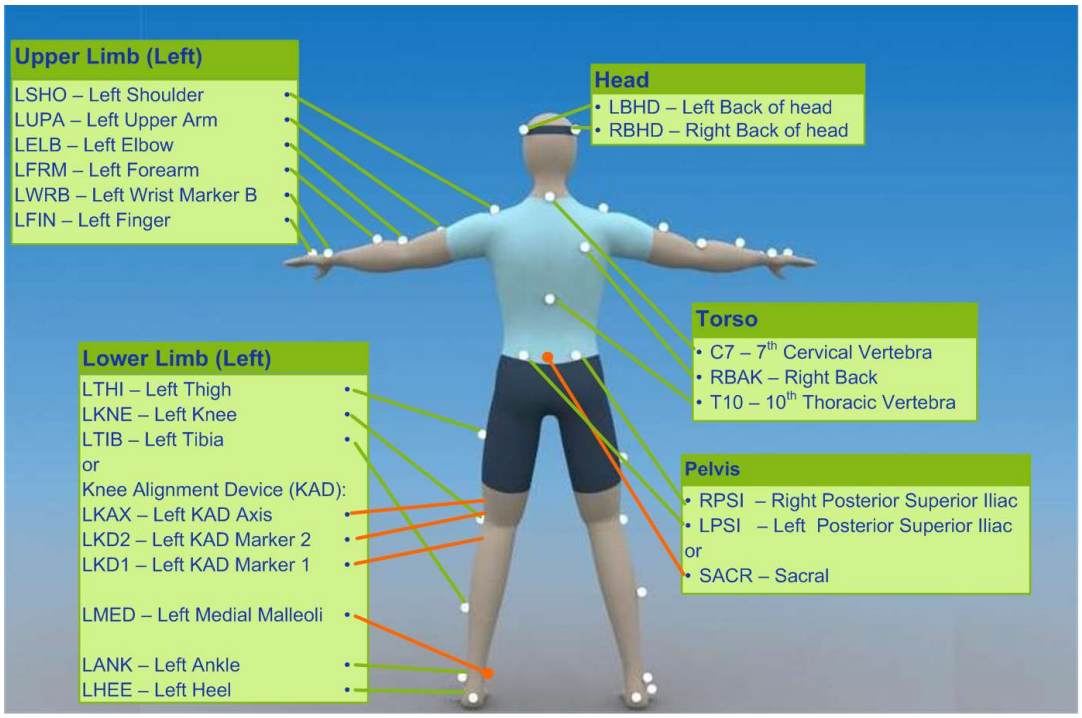


Figure 3-3 Full body marker placement back view (Vicon, 2024)

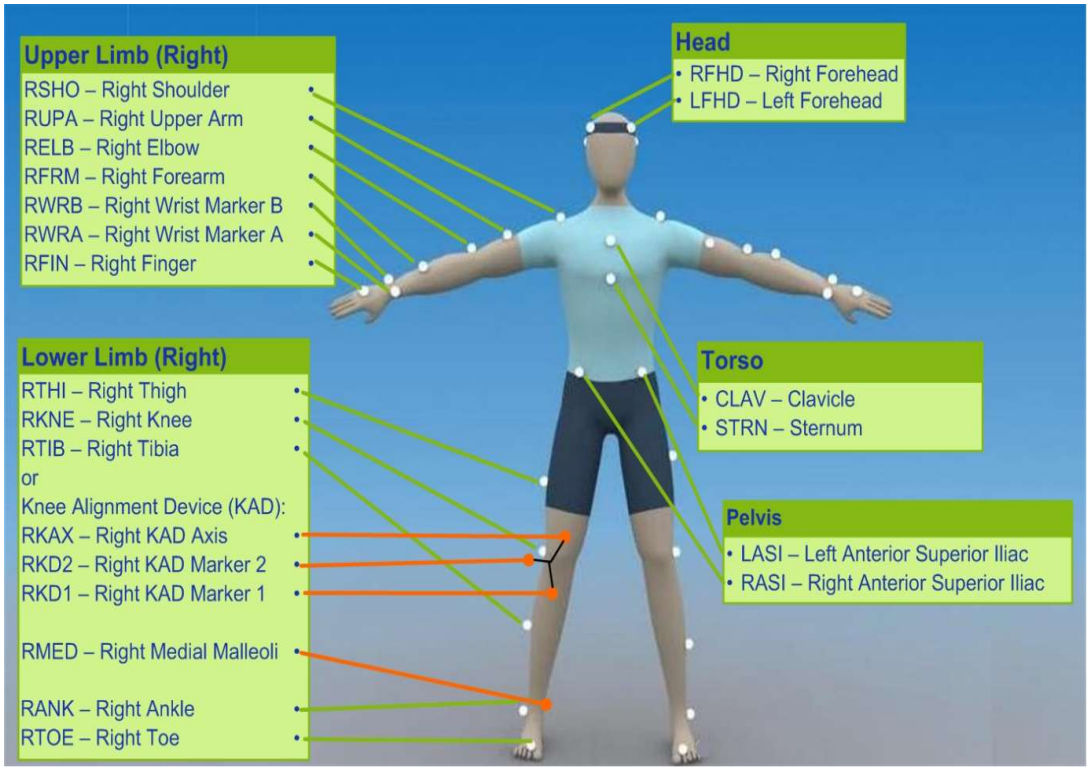


Figure 3-4 Full body marker placement front view (Vicon, 2024)

Due to the combined data collection procedure, five researchers from the ABIRA (Acquired Brain Injury Rehabilitation Alliance) team shared responsibility for collecting data across the three studies. I was one of the researchers directly involved in two of these studies, including the present one. To manage the workload efficiently, my colleague and I took turns working in the laboratory. The researcher on duty was responsible for overseeing data collection for both projects. The remaining three researchers rotated their time in the lab to focus on the third study, which used a markerless device. They also provided technical support for the two projects I was involved in.

For the Sit-to-Walk (STW) tests, which were part of one of the first two studies, two researchers were involved in data collection. Each was responsible for collecting data from approximately half of the participants. To minimise inter-rater variability, strict protocols were followed, and both researchers received thorough training on all measurement procedures, including marker placement. I was present in the laboratory for around half of the sessions. These involved the same participants across two testing sessions, which helped reduce the risk of inter-rater variability in marker placement and related procedures. Although consistent involvement of the same rater can support test-retest reliability, it does not fully eliminate the possibility of intra-rater variability.

3.2.6.1 Trial Design

Participants initiated the task from a seated position on an adjustable plinth, with their feet placed on force plates. A standard-height table with a telephone placed three meters in front of them served as the target. The plinth's height was adjusted to match the length of each participant's shank, and this height was recorded.

Participants were seated in this position so that the position allowed for a 90-degree angle at their hips, knees, and ankles, with support for the proximal half of their femurs. They were requested to sit upright, with their heads held directly above their pelvis. To avoid using their hands to assist in rising from the plinth, participants either crossed their arms over their chest or kept their arms by their sides, with elbows flexed (Figure 3-5).

Continuing with this setup, the feet were placed at a comfortable distance apart. The only requirement was that they remained on the force plate. To maintain consistency, the medial

and anterior distances between the shoes and the edges of the force plates were recorded. For example, on the right foot, the closest point between the shoe and the left edge of the force plate was measured. Similarly, the closest point between the front of the shoe and the front edge of the force plate was also noted. However, these measurements were omitted during later trials to reduce the overall trial time.

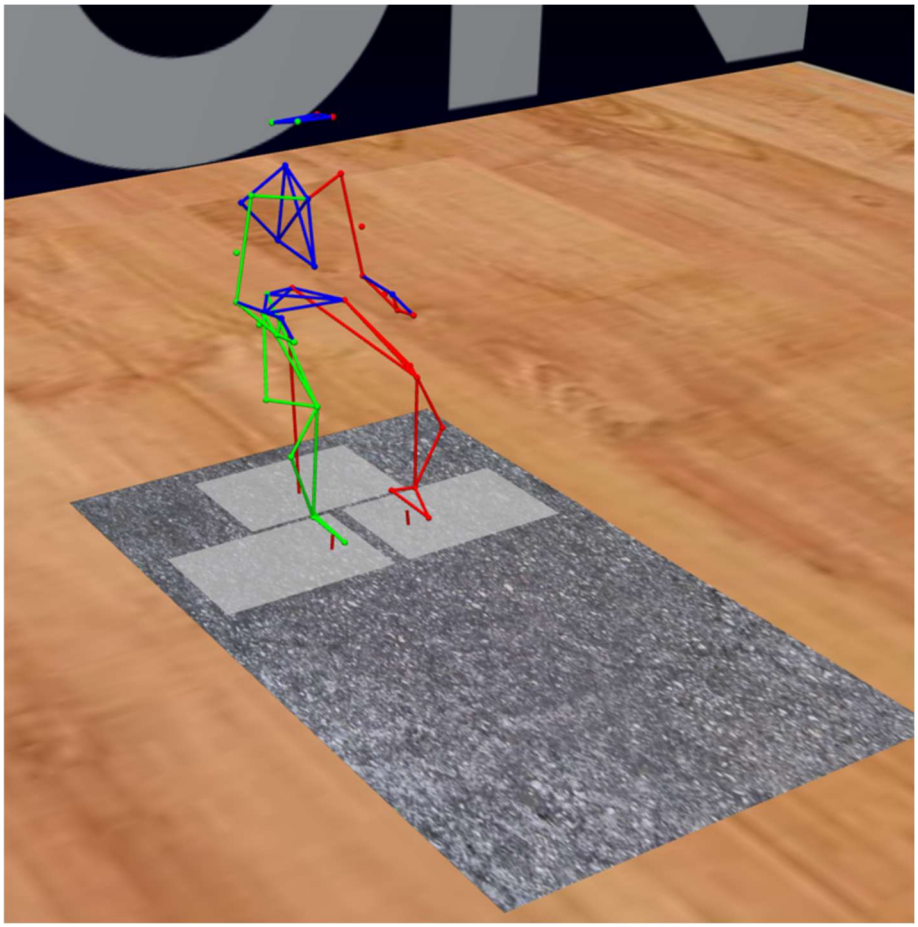


Figure 3-5 STW trial starting position from Vicon system

The task was to rise from the plinth to answer the telephone on the table. Participants were instructed to commence the task upon hearing a buzzer, with the direction, "Go and answer the telephone when you hear the buzzer. The buzzer is your signal to start the task". This instruction was intentionally focused on the task's overall goal rather than movement patterns, promoting natural and fluent movement, as detailed movement instructions might lead to unnatural or segmented motions. Through this approach, it was aimed to capture realistic movement patterns. Participants practised the task before data collection began, and data collection commenced when participants felt comfortable with the procedure.

Initially, participants completed ten trials of the task. However, after adding two cameras, the protocol was modified to include five trials, with verification of marker visibility for each trial. This adjustment was made to maintain data quality. The procedure was repeated in the second session, which was scheduled between one and four weeks after the first session, without repeating anthropometric measurements.

3.2.7 Data Processing

The captured data were processed through Nexus 7 software, which also allows for labelling each marker and eliminating 'ghost' markers. This software can merge the 2D marker positions from each camera to create a digital 3D model of the marker trajectories. System calibration is completed before the participant arrives in the lab. A five-marker calibration wand is used to scan the motion capture volume and set the volume origin of the cameras. This software further enables the use of biomechanical models, such as Plug-in Gait®, to compute various body segment kinematics (version 2.6.2, Vicon, Oxford, UK).

After the data collection, preliminary data processing was carried out through a specialised pipeline. The pipeline included the following functions:

- **Data Import:** The raw data captured from the Vicon system was initially imported for processing.
- **Data Labelling:** Markers were then assigned to specific anatomical landmarks or body segments as per the research design.
- **Gap Filling:** Any gaps in the data where markers were occluded or temporarily lost were interpolated to provide a complete data set according to guidelines
- **Coordinate Systems:** Anatomical coordinate systems were established based on the labelled markers.
- **Process:** Processing dynamic plug-in gait model on the raw data
- **Data Smoothing:** Butterworth, a smoothing algorithm, was applied to both the kinematic and kinetic data to eliminate any remaining inconsistencies.
- **Data Export:** Finally, the processed data was exported for subsequent in-depth analysis (Vicon, 2024).

Upon completion of preliminary data processing, the data was exported to MATLAB (Matrix Laboratory), a high-level computing environment, for subsequent analysis.

3.2.7.1 Metrics Extraction

MATLAB scripts were developed in collaboration with a Clinical Movement Analyst to extract metrics from the processed Vicon data. The focus was on three key variables of movement fluency: smoothness-SPARC, coordination, and hesitation.

Smoothness was evaluated using the Spectral Arc Length (SPARC) method, calculated from the Fourier magnitude spectrum of a given velocity profile (Melendez-Calderon, Shirota and Balasubramanian, 2021). To gauge movement smoothness, this analysis examines the energy content of the movement characterised by jerkiness. Lower smoothness tends to have more high-frequency energy, whereas smoother movements have less. SPARC is a recommended metric for measuring the smoothness of reach-to-grasp tasks, particularly following stroke (Koo and Li, 2016). However, it is applicable to various types of movements (Balasubramanian et al., 2015). It has been used to distinguish gait smoothness in individuals with Parkinson's disease and the control group (Yamamoto *et al.*, 2021) and between older adults who are prone to falls (Figueiredo *et al.*, 2020). The smoothness-SPARC calculation was made using open-source MATLAB scripts (Mohamed Refai *et al.*, 2021). A higher (less negative) SPARC value indicates greater movement fluency.

Hesitation during the sit-to-walk (STW) trials was defined as the maximum decrease in forward velocity of the centre of mass (CoM), expressed as a percentage of the peak value. This measure quantifies movement hesitation by noting the percentage drop in the forward movement of the centre of mass during STW, which is currently the only known method for objectively assessing hesitation during movement (Kerr *et al.*, 2013). As people age, the necessity to pause between tasks might compensate for the reduced neuromuscular-skeletal reserve (Van Der Kruk *et al.*, 2021), indicating more pronounced hesitation with higher values.

Coordination was assessed by evaluating the overlap in movement between the knee and hip in the sagittal plane during two specific phases. The first phase, referred to as

'coordination 1,' spans the period from the end of initial hip flexion to the beginning of knee extension—essentially the time frame during which both movements co-occur. The second phase, termed 'coordination 2,' covers the period from the end of hip extension during rising to the beginning of knee flexion, again focusing on the time frame when these movements overlap. According to Kerr et al. (2013), higher values in these measurements indicate better coordination between the movements.

Graphs in Figure 3-6 is based on a real data from this study and serves as a sample to illustrate how hesitation and coordination are visualised following the execution of the code.

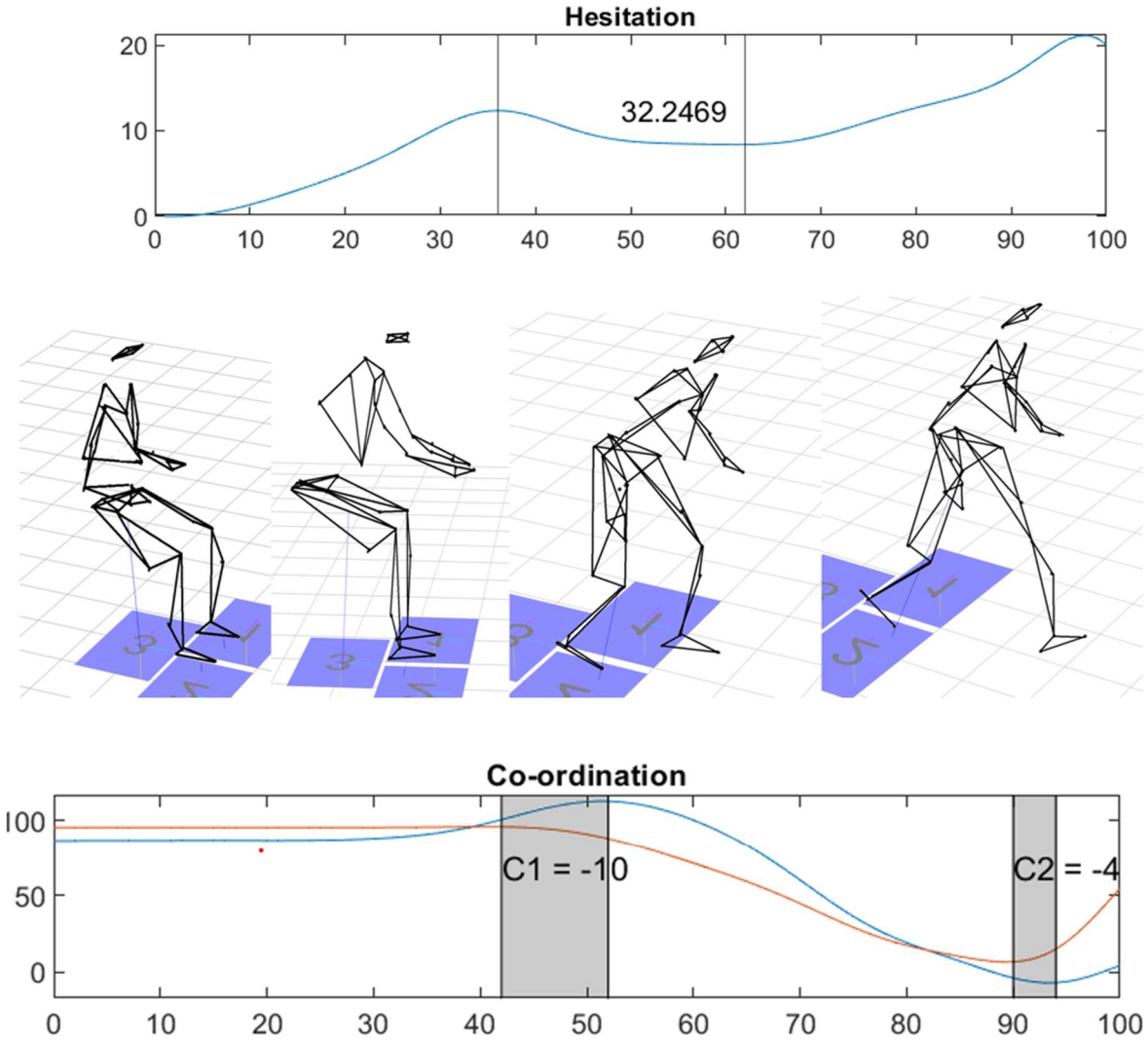


Figure 3-6 STW illustration with coordination and hesitation graphs

3.2.8 Statistical Analysis

The statistical analysis of this study aims to assess test-retest reliability and sensitivity of biomechanical metrics of the sit-to-walk task. Descriptive statistics were calculated for each session's variables (Hesitation, Coordination 1, Coordination 2, and Smoothness) to assess test-retest reliability. These statistics included the mean, standard deviation, minimum, maximum, and variance (Atkinson and Nevill, 1998).

The Intraclass Correlation Coefficient (ICC) was calculated with a two-way random effects model to assess the test-retest reliability of the neuro-mechanical measurements over two sessions (Atkinson and Nevill, 1998). The ICC and its 95% confidence intervals were calculated to evaluate the repeatability of measures across the sessions. ICC values ranging from 0.75 to 0.90 indicate good reliability, and values greater than 0.90 suggest excellent reliability (Koo and Li, 2016).

The Coefficient of Variation (CV) is the ratio of the standard deviation to the mean for each variable (Albert, 1992). It was calculated to quantify the variability of each biomechanical measure within participants. Standard Error of Measurement (SEM) and the Smallest Detectable Change (SDC) were analysed to determine the sensitivity of the biomechanical metrics to detect meaningful changes (Lexell and Downham, 2005).

The SEM was derived for each variable using the formula $SEM = SD \times \sqrt{(1 - ICC)}$, measuring the precision of individual scores if the measurement was repeated under identical conditions (Thomas and Nelson, 1996). Subsequently, the SDC was calculated using the formula $SDC = SEM \times 1.96 \times \sqrt{2}$, representing the smallest change in the measurement that can be detected beyond the error margin at a 95% confidence level (Beckerman *et al.*, 2001). SDC values are converted as percentages for a more straightforward interpretation using this formula: SDC%= (Absolute SDC/Baseline measurement) *100 (Fleiss, 1999).

To assess recovery rate, fluency metrics from STW between stroke and non-stroke populations were compared using t-tests for normally distributed variables, while Mann-Whitney U tests were used for non-normally distributed data. Then, Paired t-tests were applied for normally distributed variables to assess differences between the two sessions, while the Wilcoxon Signed-Rank Test was used for non-normally distributed variables.

3.3 Results

3.3.1 Participant Recruitment and Demographics

This study met its recruitment goal by enrolling 75 participants, 46 females and 29 males. The age range of the group was wide, with an average age of 47.8 and a standard deviation

of 17.4, from 20.5 to 85.4. Table 3-1 shows the participants' complete demographic information.

Table 3-1 Participant demographics

Description	Data
Total Participants	75 (non-stroke)
Age (years)	Mean (SD): 47.8 (17.4), Range: 20.5 – 85.4
Sex - Male: Female	29: 46
Dominant Side - Right: Left	67: 08
Body Mass (kg)	Mean (SD): 72.6 (14.1), Range: 45.3 – 114.9
Height (cm)	Mean (SD): 170.5 (9.5), Range: 152.6 – 200.6

All participants completed the initial data collection session. However, by the time of the second session, the cohort had decreased slightly, with a 4% dropout rate (3 participants). This was due to participants being unresponsive to contact attempts or unavailable during the scheduled session time.

3.3.2 Data Collection Challenges and Trial Quality

The quality and usability of the collected data were subject to variability due to complex technical challenges, impacting the number of trials eligible for final statistical analysis. The most common challenges included:

- **Visibility Issues:** Occasional invisibility of the reflective markers on the Vicon motion capture system, particularly with the sternum and hip markers, occurred due to leaning forward to start the sit-to-walk (STW) task.
- **Misplacement During Movement:** Some participants moved their feet outside the designated force plates; therefore, their data was lost.
- **Incompatibility with Extraction Codes:** The variability in participant movements sometimes exceeded the parameters set by the data extraction codes, leading to errors in code extractions.

These challenges reduced the amount of usable data, resulting in a range of 205 to 316 high-quality trials for each variable across two sessions. The mean values derived from these quality trials for each kinematic metric are detailed in Table 3-2 .

Table 3-2: Trial data summary

Variables	Session 1		Session 2	
	N/ Total Trials	$\bar{x}$ n trials	N / Total Trials	$\bar{x}$ n trials
Hesitation	50/ 205	4.1	52 / 255	4.9
Coordination 1	50/ 206	4.12	51 / 238	4.67
Coordination 2	50/ 207	4.14	52 / 248	4.77
Smoothness	63/ 289	5.78	63 / 316	6.08

Abbreviations: N= Number of Subjects; $\bar{x}$ n trials = mean number of trials per subject

3.3.3 Descriptive Statistics of Biomechanical Variables

The study conducted analyses over two sessions using the Vicon motion analysis system to assess test-retest reliability. Descriptive statistics for the biomechanical variables are presented in Table 3-3.

Table 3-3: Descriptive statistics of biomechanical variables

	Variables	N	Min	Max	Mean	Std. Dev.
Session 1	Coordination 1	50	4.25	38.60	17.08	8.69
	Coordination 2	50	-10.33	-1.00	-5.43	2.15
	Smoothness	63	-3.16	-1.80	-2.14	0.27
	Hesitation	50	3.98	88.60	30.59	14.28
Session 2	Coordination 1	51	2.00	42.40	18.61	8.30
	Smoothness	63	-2.77	-1.79	-2.13	0.21
	Coordination 2	52	-10.80	-1.50	-5.29	2.00
	Hesitation	52	7.68	72.24	32.11	13.55

N: Sample Size, Min: Minimum Value, Max: Maximum Value, Std. Dev.: Standard Deviation

Coordination Measures: During Session One, Coordination1 demonstrated variability with values ranging from 4.25 to 38.60 and a mean of 17.08. In contrast, Coordination2 showed less variability, with a narrower range from -10.33 to -1.00 and a mean of -5.43. In Session Two, Coordination1 values ranged from 2.00 to 42.40, similar in variability to the first session, with a mean of 18.61. Coordination2 maintained similar consistency to the first session, with values from -10.80 to -1.50 and a mean of -5.29.

Smoothness of Movement: Both sessions demonstrated small variability in the smoothness of movement. Session 1 had a narrow range from -3.16 to -1.80, with a mean of -2.14, while Session 2 ranged from -2.77 to -1.79, with a mean of -2.13.

Hesitation: Hesitation showed a range of diversity in both sessions. In the first session, values ranged widely from 3.98 to 88.60, with a mean of 30.59. The second session showed a similar pattern, with values from 7.68 to 72.24 and a mean of 32.11. The wide range of hesitation data (3.98-88.60) in Table 3.3 can be attributed to the study design, which accepted all Sit-to-Walk (STW) trials as long as participants did not stop after standing up (STS) and before initiating walking. The instructions emphasised focusing on the target to encourage natural movement, thus aiming to replicate real-world behaviour as closely as possible. As a result, the variation in the hesitation index is likely reflective of individual differences in participants' movement strategies, decision-making, and physical capacities. These factors contribute to considerable variability in the time taken to transition from standing to walking, as participants may adopt different paces based on their personal comfort and ability. This variability should be considered when interpreting the hesitation data, as it suggests that the measurement channel is sensitive to individual differences and the natural variation inherent in functional movements.

3.3.4 Test-retest Reliability of Biomechanical Measurements

The test-retest reliability of the biomechanical variables was assessed using Intraclass Correlation Coefficients (ICCs) with a two-way random effects model. ICCs are widely recognised as a robust measure of reliability, particularly when repeated measurements are taken under similar conditions, as they assess the consistency of measurements across sessions (Koo & Li, 2016). The choice of a two-way random effects model is appropriate when both the participant effects and measurement effects are assumed to be random

(Shrout and Fleiss, 1979). This approach aligns with the need to evaluate variability not just between participants but also within participants across repeated measures. This model assumes that both participant effects and measurement effects are random. Type A ICCs were calculated based on the absolute agreement definition, providing a robust measure of repeatability across sessions (McGraw and Wong, 1996). The use of Type A ICCs based on absolute agreement is well-documented in studies where precision and repeatability across sessions are of primary concern. Absolute agreement ICCs are considered more stringent than other ICC types as they require exact match between measurements across repeated tests (Koo & Li, 2016).

The results, summarised in Table 3-4, include ICC values, 95% confidence intervals, F-test statistics, degrees of freedom (df1 and df2), and corresponding p-values. The F-test evaluates the ratio of variances, and the p-values determine the statistical significance of the ICCs against a null hypothesis of zero reliability. The degrees of freedom reflect the number of participants and matched observations in each condition.

Table 3-4: Intraclass Correlation Coefficients (ICC) for biomechanical Variables

Variable	ICC	95% Confidence Interval	F Test			
			Value	df1	df2	Sig
Coordination2	0.608	0.286 – 0.785	2.564	43	43	0.001
Hesitation	0.744	0.529 – 0.861	3.844	43	43	<.001
Coordination1	0.642	0.349 – 0.805	2.879	42	42	<.001
Smoothness	0.702	0.499 – 0.823	3.335	58	58	<.001

Sig: significant, df1 and df2: degrees of freedom

None of the variables—Hesitation, Smoothness, Coordination1, or Coordination2—met the criteria for acceptable test-retest reliability, defined as an ICC between 0.75 and 0.90 with a lower 95% confidence interval (CI) of at least 0.70 (Portney and Watkins, 2009). The lower bounds of the confidence intervals for all variables indicate substantial variability in measurements across sessions.

Hesitation had the best reliability (ICC = 0.744), but its lower 95% CI was 0.529, failing to meet the required threshold of 0.70. Smoothness recorded an ICC of 0.702, with a lower 95% CI of 0.499, indicating variability that compromises its test-retest reliability. Coordination1 showed an ICC of 0.642, with a lower 95% CI of 0.349, while Coordination2 had an ICC of 0.608, with a lower 95% CI of 0.286.

3.3.5 Analysis of Measurement Variability

In this study, the Coefficient of Variation (CV) were used to measure the variation in each biomechanical measure separately in each session, which facilitates understanding the relative spread of data points around their mean values. Table 3-5 summarises the CV for each metric calculated from the standard deviation (SD) and mean values obtained during the study.

Table 3-5: Coefficient of Variation (CV) for biomechanical measures

Variables	Session 1		Session 2	
	CV (%)	N	CV (%)	N
Hesitation	46.68	50	42.20	52
Smoothness	12.54	63	10.02	63
Coordination1	50.86	50	44.59	51
Coordination2	39.60	50	37.83	52

N: Sample size, Coefficient of Variation (CV)

The Coefficient of Variation (CV) analysis was measured across two sessions separately from the data session one and session two; the results of this analysis revealed the following findings:

- **Hesitation:** The analysis showed high CV values in both sessions, with 46.68% in Session 1 and 42.20% in Session 2. These results indicate variability in the participants' hesitation before initiating the gait.
- **Smoothness:** The analysis revealed considerably lower CV values, recorded at 12.54% in Session 1 and 10.02% in Session 2.
- **Coordination:** Coordination1 exhibited higher variability with a CV of 50.86% in Session 1 and 44.59% in Session 2. Coordination2 showed CVs of 39.60% in Session 1 and 37.83% in Session 2.

3.3.6 Sensitivity to Change

The study aimed to determine the sensitivity of the Vicon system in detecting meaningful changes in neuro-biomechanical measures. For this aim, the smallest detectable change (SDC) was calculated. The SDC was determined by computing the Standard Error of Measurement (SEM) and the Intraclass Correlation Coefficient (ICC). Please refer to the methodology section for the formula.

3.3.6.1 SEM and SDC Calculations

- **Standard Error of Measurement (SEM)**: SEM was calculated for each variable to reflect the precision of individual scores around a hypothesised "true" value in the population.
- **Smallest Detectable Change (SDC)**: SDC represents the smallest change in a measure that can be detected, distinct from measurement error, indicating the practical threshold for change detection in research settings. These values are represented in Table 3-6.

Table 3-6: SDC (smallest detectable Change) and SEM (Standard error of measurement) values for biomechanical variables

Variables	SEM	SDC (%)
Hesitation	7.04	62.25
Smoothness	0.13	17.07
Coordination1	5.08	78.93
Coordination2	1.30	67.20

Hesitation: Displayed a significant SEM of 7.04, leading to a relatively high MDC of 62.25%, which indicates that a notably larger change is required to surpass the threshold of measurement error, reflecting the substantial variability observed in this measure.

Smoothness: It showed a low SEM of 0.13 and an MDC of 17.07%, suggesting that smaller changes in smoothness can be reliably detected.

Coordination: These measures exhibited higher values of SEM and MDC, particularly for Coordination1 (SEM: 5.08; MDC: 78.93%) compared to Coordination2 (SEM: 1.30; MDC: 67.20%).

3.3.7 Comparison of Motor Function between Control and Stroke Survivors at Baseline

One of the objectives was to compare sit-to-walk (STW) fluency metrics between stroke and non-stroke participants to better understand motor function. To address this objective, motor function was measured using biomechanical analyses in stroke and non-stroke groups, and they were compared.

Motor function is assessed using sit-to-walk (STW) fluency metrics, which evaluate the transition from sitting to walking. Movement fluency was compared with non-stroke participants to gauge stroke recovery progress. Statistical comparisons were conducted using **T-tests** for normally distributed data and **Mann-Whitney U tests** for non-normally distributed data, ensuring a robust analysis of movement quality differences (Table 3-7).

Table 3-7 Comparison of motor function between control and stroke survivors at baseline

	Variables	Non-stroke		Stroke		p-value
		N	Mean (SD)	N	Mean (SD)	
	Age	75	47.77 (17.43)	44	62.34 (12.37)	<0.001*
Session 1	Coordination-1	50	17.08 (8.69)	29	16.42 (7.41)	0.732
	Coordination-2	50	-5.43 (2.15)	29	-5.39 (2.46)	0.938
	Hesitation	50	30.59 (14.28)	29	45.45 (19.80)	<0.001*
	Smoothness	63	-2.14 (0.27)	30	-2.28 (0.28)	0.01*
Session 2	Coordination-1	51	18.61 (8.30)	24	13.57 (7.67)	0.014*
	Coordination-2	52	-5.29 (2.00)	24	-5.68 (2.57)	0.476
	Hesitation	52	32.11 (13.55)	24	43.12 (19.34)	0.017*
	Smoothness	63	-2.13 (0.21)	24	-2.25 (0.29)	0.048*

Highlighted p-values are tested by Mann-Whitney Test
N number of trials
*Significant results

The analysis compared the non-stroke and stroke groups across several variables, and it reveals significant differences in some key metrics. Regarding **age**, the stroke group had a significantly higher mean age (62.34 ± 12.37 years) compared to the non-stroke group (47.77 ± 17.43 years).

In **Session 1** (Table 3-7)**,** no significant difference was found in **Coordination-1** and **Coordination-2** between the non-stroke and stroke groups. However, the stroke group exhibited significantly higher **hesitation** (45.45 ± 19.80) compared to the non-stroke group (30.59 ± 14.28). Additionally, **smoothness** was lower in the stroke group (-2.28 ± 0.28) than in the non-stroke group (-2.14 ± 0.27).

In **Session 2** (Table 3-7), a significant difference was observed in **Coordination-1**, where the stroke group (13.57 ± 7.67) showed lower scores than the non-stroke group (18.61 ± 8.30), with a p-value of 0.014. For **Coordination-2**, no significant difference was found between groups. Once again, the stroke group demonstrated significantly higher **hesitation** (43.12 ± 19.34) compared to the non-stroke group (32.11 ± 13.55), with a p-value of 0.017. Lastly,

stroke participants had significantly lower **smoothness** (-2.25 ± 0.29) levels in STW compared to the non-stroke group (-2.13 ± 0.21), with a p-value of 0.048.

3.4 Discussion

3.4.1 Discussion of Findings in Context of Previous Research

The test-retest reliability for the fluency metrics from sit-to-walk (STW) in non-stroke group failed to reach clinically acceptable levels. Lack of adequate test-retest reliability suggests that the repeatability of these measures over two sessions is insufficient. Thus, it raise questions regarding their reliability in clinical contexts. Additionally, smoothness is more sensitive to detecting small changes, while the other variables require larger changes to be noticeable. Motor function in stroke participants was assessed across two sessions and compared with non-stroke participants from a test-retest reliability study. Significant differences were observed in all biomechanical variables except for coordination-2, which was also found to be the least reliable variable in the test-retest study. However, due to COVID-19 constraints, the non-stroke participants in the test-retest reliability study were not age-matched with the stroke participants.

The test-retest reliability of the SPARC (Spectral Arc Length) metric in measuring smoothness during sit-to-walk transitions has not been explored yet. Therefore, reliability studies are from the studies focused on the upper extremities. Bayle et al. (2022) investigated the inter- and intra-subject reliability of smoothness in upper extremity reaching movements using the SPARC metric. Their findings further highlight the robustness of this measure. Among the various smoothness metrics evaluated, SPARC demonstrated the lowest variability both between subjects (coefficient of variation calculated between subjects ranging from 1.6% to 2.2%) and within subjects (coefficient of variation calculated between tries ranging from 1.6% to 1.9%). This consistency and reduced variability make SPARC particularly suitable for research involving highly impaired individuals who may only be able to perform a limited number of movement repetitions. Similarly, the test-retest reliability of SPARC values (Cornec *et al.*, 2024) in stroke participants showed excellent intraclass correlation coefficients (ICCs) of 0.912 [0.861; 0.946]. These metrics were the only ones to achieve excellent reliability (ICC > 0.9) while also maintaining a low measurement error (coefficient of variation < 10%). However, in our study, The ICC for

smoothness-SPARC in the sit-to-walk task was found to be 0.70 [0.50–0.82], indicating moderate reliability.

Engdahl and Gates, (2019) measured the test-retest reliability of SPARC, focusing on Smoothness-SPARC during six functional reaching tasks. They reported the test-retest reliability of SPARC smoothness values as ICC = 0.81. This value indicates better reliability compared to our study, where the ICC for this metric was 0.702. Additionally, the between-session SDC value of 11% reported in their study is smaller than the corresponding value found in our study.

This difference in reliability may stem from the type of movement measured in these studies. Reaching tasks were shown to inherit less variation compared to object manipulation, which allows more flexibility for target movement. Similarly, whole- body movements like STW are open to more variability in movements. It also includes more sub-movements compared to reaching tasks, and the number of sub-movements consistently was linked to lower reliability (Engdahl and Gates, 2019).

Further investigation into the clinically unacceptable test-retest reliability may reveal that it is due to a combination of factors. These include the potential unsuitability of fluency metrics from STW for kinematic analysis by video-based systems, the natural variability in human movement, and the combined effects of the experimental setup and lab environment. Additionally, the limitations of this study, detailed in the following section, may have also played a role. Together, these factors likely contributed to the observed low reliability.

First, kinematic metrics derived from video-based systems, other than Smoothness-SPARC (Bayle et al., 2022; Cornec et al., 2024) might be unreliable. A systematic review on kinematic assessments of upper limb supports this: It found that only one metric, peak velocity, met adequate clinical standards for test-retest reliability. This was out of 30 metrics that were investigated (Schwarz *et al.*, 2019). This aligns with Engdahl and Gates (2019) who suggest that some variables, such as maximum joint angles, may be more reliable because they are calculated directly from positional data at a single point in time. In contrast, movement quality metrics for functional tasks, which are derived from continuous positional data or their derivatives, are more sensitive to small changes in

performance. As a result, they tend to exhibit greater variability. Nonetheless, kinematic metrics during functional tasks are more relevant to stroke rehabilitation than those derived from isolated limb movements (Deane *et al.*, 2020). Supporting the focus on analysing kinematics during functional tasks, a study on joint angles during gait and sit-to-stand movements found excellent reliability in the sagittal plane, with ICC values above 0.80 for most joint angles. However, the study noted that systematic errors and variability remained in sit-to-stand tasks (Deane *et al.*, 2020). It suggests that not all kinematic metrics during functional tasks exhibit acceptable test-retest reliability. The complexity of the movement itself can be a disadvantage, as noted in a previous study (Tamura, Tanaka and Kawanishi, 2020). On top of that, movement quality metrics are highly sensitive to small changes in performance because they are derived from continuous positional data. While this sensitivity makes them more responsive, it also increases variability. These metrics are particularly vulnerable to signal noise and data processing effects, such as filtering, because they rely on rates of change (e.g., differences between consecutive data points). As a result, small inconsistencies in the data can be amplified, leading to less consistent measurements across sessions or trials (Engdahl and Gates, 2019). In the same vein, fluency metrics, which are also derived from continuous positional data, are highly sensitive to subtle variations in performance, signal noise, or differences in the experimental setup.

The second potential reason for the clinically unacceptable test-retest reliability in this study, might stem from the inherent variability of human movement, which aligns with the concept known as the "bliss of motor abundance" (Latash, 2012). This principle challenges the traditional view of motor control, which considers motor redundancy a problem to be solved through optimisation. Instead, it states that the seemingly redundant degrees of freedom in human movement are not only beneficial but essential for adapting to various conditions and tasks (Latash, 2012). For instance, the present study revealed significant intra-participant variability, with metrics such as coordination showing variability as high as 41% of the mean coefficient of variation (CV) in an individual's trials and hesitation reaching up to 47%. Smoothness was relatively more stable at a max of 13%, probably due to being less related to different strategies adopted and more focused on the energy expenditure on the movement. Variability in movement strategies during the STW task, along with the movement boundary limits set by the trial design, may have affected the reliability of specific kinematic metrics.

Participants in our study were instructed to keep their feet within the force plates. However, foot movements were not restricted if the feet remained within the boundaries of the force plates. This allowed some participants to slightly move one foot backwards at the start of the sit-to-walk (STW) task, a behaviour previously observed in research (Perera *et al.*, 2023). In contrast, some participants chose not to move their feet. These variations in foot placement, along with the potential differences in body movement, highlight how initial conditions can influence biomechanics (Perera *et al.*, 2023, p. 202; Miller, Van Der Kruk and Silverman, 2024). For example, narrow foot positions led to smaller body centre of mass (CoM) displacement compared to wider foot positions, which were associated with different ground reaction forces (GRFs) and strategies for lateral body COM control (Miller, Van Der Kruk and Silverman, 2024). Additionally, participants were prevented from using their hands for assistance when standing up. Despite this, they employed different strategies: some used their arms and trunk to generate momentum, while others relied more on their lower extremities for power (Perera *et al.*, 2023). These differences in movement strategies—whether in foot placement, arm use, or trunk involvement—could contribute to variability in the biomechanics of the STW transition, which may impact test-retest reliability.

Smoothness is less influenced by variations in movement strategies, making it a more reliable metric compared with other variables in this study. However, the reliability of this metric was below clinically acceptable levels (>0.75) (Portney and Watkins, 2009). Hesitation, as measured by a drop in speed during transitions (Kerr *et al.*, 2013), can be influenced by several factors that may resemble hesitation but are not directly related. For instance, if they focus more on carefully navigating their surroundings than prioritising walking speed, they might intentionally slow down their transition. Additionally, the controlled nature of a lab environment can further contribute to hesitation. Participants may become overly conscious of the motion-tracking markers and take extra care not to dislodge them, which can alter their natural movement patterns. While participants might be capable of smoother transitions with minimal speed drops, unless their maximum performance was evaluated within a context where they feel comfortable and secure, hesitation values will likely remain inconsistent, even within the same individual (Jones *et al.*, 2021).

3.4.2 Limitations and Strengths

This study has several limitations. First, the trial design may have introduced variability that affected measurement repeatability. Although participants were instructed not to use their arms, arm positions were not strictly standardised across trials. This lack of control may have contributed to variability in the data, as differences in arm positioning could have influenced the participants' centre of mass, which plays a role in the measurements. Consequently, it is difficult to determine whether observed differences were due to experimental conditions or variations in arm placement, impacting the reliability and validity of the results. Despite the variability caused by methodological limitations, the sample size, determined through a power calculation, was successfully attained.

The initial positioning of participants was visually assessed rather than objectively measured, introducing another source of potential variability. Participants placed their feet at a comfortable distance from each other, provided both feet were positioned on the force plate. Medial and anterior distances between the shoes and force plate edges were initially recorded to maintain consistency. However, to reduce trial time and minimise participant fatigue, these precise foot measurements were later omitted. While this adjustment improved procedural efficiency, it may have increased variability in foot placement across trials, affecting data consistency. This trade-off between precision and practicality should be considered when interpreting the reliability of the findings.

Another possible reason for low test-retest reliability could be inadequate numbers of trials. While the current recommendation of 2-5 trials for a drinking task seems adequate (Frykberg, Grip and Alt Murphy, 2021), the appropriate number of trials required to account for intra-participant variability in tasks like STW remains uncertain. Research on gait initiation, for instance, has indicated that the number of trials required to achieve a reliable intraclass correlation coefficient ranges from 1 to 10 trials depending on the specific metric (Seuthe *et al.*, 2021). Without specific data on STW, drawing a definitive conclusion on the required number of trials is challenging. Therefore, another limitation could be the uncertainty regarding the optimal number of trials for reliable STW metrics. The two to five trials applied in this study may not have been enough to capture intra-participant variability effectively, especially for complex tasks like STW.

Marker placement differences also can induce some variability in the data. In the initial phase of this methodology, two operators were responsible for placing the markers. As a result, much of the early data did not meet quality standards due to large gaps in the recordings. However, around after the first 10 participants, this procedure changed, coinciding with the addition of two cameras. Subsequently, the marker placement for most of the participant's first and second sessions was conducted by a single operator, which improved the reliability of the data.

In this study, a full-body marker set was used to assess movement and accurately calculate the centre of mass (CoM), which was necessary to measure hesitation during the sit-to-walk (STW) task. Hesitation was defined as the largest drop in forward CoM velocity, expressed as a percentage of its peak value, based on the method described by Kerr et al. (2013). A full-body model was required because accurate CoM calculation in the Vicon motion capture system depends on markers placed on the head and thorax, which are not included in lower-limb-only models (Vicon, 2024). In addition, the data collection was part of a larger research programme involving three related studies, some of which focused on upper limb movements. Using a full-body marker set ensured consistency across all studies and avoided the need to reapply or adjust markers between sessions (Vicon, 2024).

The full-body model allowed for the collection of more detailed data, but it also introduced limitations. The high number of markers increased the chance of placement errors, which can affect the accuracy and replicability of the results. However, to minimise variability, all markers were placed by trained and experienced researchers. Evidence suggests that individuals with extensive training in gait analysis or clinical movement assessment are more likely to achieve accurate and consistent marker placement (Fonseca et al., 2023).

However, the involvement of multiple operators can still introduce variability, as the precision of marker placement tends to differ between individuals (Fonseca *et al.*, 2023). Even slight differences in marker placement can lead to discrepancies in the kinematic data, which potentially affects the repeatability of the measurements. Despite this, the expertise of the operators in this study likely minimised such variability and helped ensure more reliable results.

The duration of the sessions was around one hour, including 10 STW trials. However, when the protocol was adjusted to include five trials per participant, each requiring review by the researcher, the total session time was slightly reduced. While the researcher checked the data between trials, participants were allowed to rest. Although longer sessions can potentially lead to fatigue, the actual active time required from participants was limited. In addition, participants were regularly asked whether they wished to take a break. This allowed them to manage their comfort and reduce the risk of fatigue. These measures helped ensure participants remained focused and performed consistently throughout the testing process.

The potential for variability was further mitigated in smoothness-SPARC metrics, as this metric was not derived from either the centre of mass or joint angles—areas typically susceptible to variability due to marker placement (Fonseca *et al.*, 2022). However, other metrics – hesitation and coordination derived from joint angles or centre of mass may be affected by marker placement. Because lower limb markers, particularly those placed on joints like the hip and knee, are often sources of variability in gait analysis (Fonseca *et al.*, 2022). Studies have shown that inaccuracies in placing markers on these anatomical landmarks can lead to significant errors in kinematic measurements. This situation is especially pronounced when measuring rotational movements of joints (McGinley *et al.*, 2009). By ensuring that the metrics used in this study were less dependent on such markers, the researchers effectively reduced the likelihood of variability impacting the study's outcomes (Fonseca *et al.*, 2022).

3.4.3 Research Implications

The reliability of fluency metrics in sit-to-walk is rarely investigated, and larger population studies are needed to set up normative data to measure and compare these metrics to clinical populations with movement impairments, such as measuring stroke recovery.

Sit-to-walk is a complex, whole-body task that inherently involves more movement variability compared to isolated movements (McGinley *et al.*, 2009). Therefore, better standardisation is needed to reduce variability. Moreover, STW movement strategies should be identified, and people need to be grouped according to these strategies.

In reflecting on the procedural and methodological changes that could enhance future studies, several key improvements have emerged based on the experiences from this study. Firstly, to reduce variability in movement execution, more standardised starting positions should be implemented. This is particularly important for foot and hip alignment. Consistently recording foot positions would support reproducibility across sessions. It would also help minimise variability caused by differences in posture or stance between trials. In addition, limiting arm movement during the Sit-to-Walk (STW) task may reduce its effect on the centre of mass (CoM). This would help ensure that the analysis remains focused on lower-body movement. Regarding the motion capture system, the use of a markerless system could offer important advantages. It would reduce the likelihood of participants becoming overly aware of the markers. This, in turn, would lower the chance of them unintentionally adjusting their movements to avoid dislodging the markers.

Participant instructions also play a critical role in reducing conscious effort during movement execution. In this study, a phone task was used during the STW trial. Participants were asked to answer the phone, which helped divert their attention from the movement itself. However, in future studies, it may be beneficial to introduce different tasks across trials to keep participants more engaged. For instance, one trial could involve answering a phone, another could involve retrieving an object, and a third might include interacting with something like a ball. This variation would encourage more natural movement. It would also help ensure that participants focus on completing the task rather than consciously monitoring how they move.

Future research should focus on evaluating the reliability of fluency metrics like SPARC in clinical populations with impaired mobility, as well as investigating strategies to reduce variability in hesitation and coordination during complex tasks. Exploring the optimal number of trials for reliable assessment in functional tasks such as sit-to-walk will also be essential.

4 Chapter 4: Study Three, The Relationship Between Motor Function and Sleep

4.1 Introduction and Objectives

Sleep is crucial to many areas of health and well-being. Emerging evidence suggests that sleep has a substantial impact on stroke. However, findings in this area remain inconsistent (Fulk *et al.*, 2020). Previous research has found that sleep disruption during inpatient rehabilitation from stroke or brain injury is associated with poorer motor outcomes (Fleming *et al.*, 2021). Some studies have reported no differences in functional outcomes between stroke survivors with or without sleep disorders post-rehabilitation. Therefore, further investigation into this link is needed (Fulk *et al.*, 2020).

Both subjective and objective measures are essential for a comprehensive and accurate evaluation of sleep. Actigraphy, as a low-cost, non-invasive, and highly tolerable method, provides an effective means of estimating objective sleep measures in natural environments (Martin and Hakim, 2011). However, due to its inherent limitations—most notably its low specificity in detecting wakefulness —studies have reported specificity levels falling below 60%. This low specificity leads to inaccuracies in sleep measurement, namely total sleep time, sleep efficiency, and wake after sleep onset (Sadeh, 2011). For this reason, the use of a sleep diary is recommended alongside actigraphy, as this combined approach enhances the reliability of sleep assessments by compensating for the shortcomings of actigraphy (Breneman *et al.*, 2024).

Kinematic analysis is a highly effective tool for assessing motor function because it reflects the quality of motor function without compensation (G Kwakkel *et al.*, 2019). While kinematic analysis is commonly suggested for detecting motor function after stroke, this is the first study that has used this method to investigate the association between sleep and motor function.

In this study, motor function was measured by movement fluency metrics, which are smoothness, coordination, and hesitation. The sit-to-walk (STW), which combines sit-to-stand and gait initiation, is regarded as an appropriate task for assessing movement fluency

(Kerr et al., 2013). Therefore, in this study, motor function after stroke was assessed based on the fluency of sit-to-walk movements.

While prior research frequently focused on subjective sleep measures or divided participants based on the presence of sleep disturbances, fewer studies have examined sleep quality and recovery outcomes as a continuum (Fleming, Smejka and Slater, 2020). This study aims to explore How sleep dimensions measured by objective and subjective are associated with motor function, considering factors such as age and mental health in continuum.

The specific research objectives are as follows:

- To understand the differences in the same variables are derived from objective versus subjective sleep measurements.
- To examine the correlation between sleep, measured by objective and subjective assessments; and motor function, evaluated through biomechanical analysis and the Fugl-Meyer Assessment, at two time points.
- To investigate the relationships between motor function outcomes and the most correlated sleep measures using a robust multivariate regression model, with adjustments for demographic and psychological factors.

4.2 Methodology

This section describes the research methods used to investigate the link between sleep patterns and recovery trajectories in stroke survivors. The methodology has several components: research design, ethical considerations, participant recruitment, sleep assessment techniques, stroke recovery measurement, data collection, and statistical analysis.

4.2.1 Research Design

This study used a longitudinal, observational cohort design with two sessions separated by 2-4 months to monitor motor improvements. Stroke patients' recovery was evaluated using biomechanical assessments (Fluency metrics from STW) and functional impairment scale

(FMA-LL). Sleep duration, continuity and quality were evaluated using validated instruments. Actigraphy, an objective method of measuring sleep, was combined with self-reported measures of sleep quality to give a comprehensive picture of the participants' sleep. Mental health assessments were incorporated as potential confounding factors in the relationship between sleep and motor function after stroke.

The Ethical approval was obtained from the UEA Faculty of Medicine and Health Ethics Committee on 26th November 2020 (Reference ID: 2020/21-028). Please find this document in Appendix 2. This approval covers the second study (test-retest reliability study of fluency metrics), as both studies have been included under the same ethics application.

The methodology of this study was similar to that used in the second study: the potential participants were informed about the study through emails, phone calls, or face-to-face meetings. During these interactions, their queries were addressed, and they were given detailed information about their right to withdraw at any point. Unlike the second study, online consent was not an option. Participants provided their consent either by postal mail or in person. All participants were required to complete allergy screening forms, and individuals allergic to latex were excluded. Consent and allergy forms were stored securely on a password-protected UEA server, aligning with document handling procedures detailed in the second study.

4.2.2 Participants

In this study, the inclusion criteria are:

- Individuals aged over 18 years and diagnosed with a stroke.
- Absence of additional neurological conditions such as Alzheimer's or Parkinson's disease.
- No latex allergy and provision of informed consent.
- Community-dwelling, discharged from NHS stroke services, and able to visit MoveExLab independently or with caregiver assistance.
- Adequate mental capacity to understand instructions and respond to questions.

The exclusion criteria include:

- Not being discharged from NHS stroke services.
- Inability to commute to MoveExLab.
- Presence of additional neurological diseases.
- Lack of mental capacity to consent or understand tasks.
- Having a latex allergy.
- Individuals who received a stroke diagnosis retrospectively, not at the time of the incident.

Retrospective stroke diagnoses were excluded due to the difficulty of verifying past medical event details. Although clinical records were not requested, all participants self-reported their stroke history. Inclusion was limited to those who had undergone clinical assessment and medical recognition of the stroke event. During screening, we asked detailed stroke histories, including the type of stroke, the affected side, and any associated symptoms. This information helped us develop a more comprehensive understanding of each case. However, such detail was not available in retrospective cases, where individuals were unaware, they had experienced a stroke. In these instances, the diagnosis was verbally reported to them based on incidental MRI findings discovered after an unspecified period. The absence of clinical context made it difficult to determine the timing and relevant data of the stroke event. Therefore, these cases were excluded to minimise the risk of misclassification and to maintain diagnostic consistency within the study.

There were no inclusion or exclusion criteria based on the level of stroke-related disability. This decision was made in response to the recruitment challenges faced during the COVID-19 pandemic. At the time, it was anticipated that obtaining a sufficient sample size would be difficult. In addition, the recruitment setting shifted from NHS patients to community-dwelling individuals. This change further influenced the decision to adopt broader eligibility criteria. While this approach may have introduced variability in disability levels, it also increased the generalisability of the findings to a wider stroke population. However, it is important to note that most participants had only mild stroke-related impairments. This should be taken into account when interpreting the study results.

To support the inclusion of individuals with a wider range of functional abilities, several additional measures were implemented. Communication difficulties were managed by giving clear and simple instructions. When necessary, researchers used body language to

aid understanding or allowed caregiver assistance. For participants with significant physical limitations, adaptations were made to the testing environment. MoveExLab provided sitting support and a patient lifting sling. These tools were available to assist individuals who needed help with posture or transferring. These adjustments helped ensure that all participants could take part safely and comfortably, regardless of their level of impairment.

4.2.2.1 Sample Size

The sample size estimation was based on a power calculation for assessing agreement. Assuming an intra-class correlation coefficient (ICC) of 0.85, a total of 54 participants would allow for estimating the ICC with a 95% confidence interval width of no more than 0.15. To ensure that at least 54 complete datasets were obtained, the recruitment target was set at 65 participants. However, due to recruitment challenges during COVID-19 pandemic, a total of 44 stroke patients were included in the final analysis.

4.2.3 Recruitment Process

The recruitment process in this study involved several channels for distributing posters, as shown in Appendix 9. The recruitment advertisement explained that the study aimed to investigate how movement recovers after stroke and whether this recovery is influenced by sleep. It informed potential participants that stroke survivors would take part in two sessions. These sessions would involve performing simple functional tasks. Specifically, participants would be asked to answer a phone from a seated position and after moving from a chair to a table. The advertisement also stated that they would complete sleep questionnaires. In addition, it mentioned that their everyday activity would be monitored using motion watches.

To disseminate these posters, relevant charities were approached first. These included the Stroke Association, Headway, and the Brain Injury Trust. These organisations assisted by distributing ethically approved posters and participant information sheets (Appendix 7). They also highlighted that the study would take place in Norwich and that travel costs would be reimbursed for distances of up to 50 miles. Second, posters were placed around Norwich Research Park and in public buildings within a 25-mile radius. Local media outlets

such as newspapers and radio stations in the same radius were also contacted. Press releases for recruitment were tailored to each communication channel. Third, study posters were disseminated through online platforms, namely the RHITE database (https://brainhtc.org/rhite/), the ABIRA website (http://www.abira.ac.uk), the HSC Bulletin, the UEA Lasdun, and social media channels like HSC Twitter. Furthermore, people who learned about the study from current participants and approached the research team directly were recruited. Participants from previous studies who had consented to be contacted for future research were also considered. These measures helped to reach a wider audience.

Upon reaching out via email or phone, interested individuals were provided with a detailed overview of the project and a participant information sheet. They were required to sign an informed consent form (Appendix 8) before participating to ensure informed and voluntary involvement in the study.

The recruitment process was designed in a way that naturally selected participants with the mental capacity required to take part in the study. Research posters were distributed through charities and other channels, and in some cases, the study was directly introduced to potential participants. After seeing the posters, individuals needed to contact the research team by email or phone to express their interest. They were also required to travel to the research lab either independently or by taxi. These steps served as a filter, as individuals who were unable to understand the study information or arrange travel were unlikely to proceed further.

In addition, participants needed to understand and sign a consent form, confirming their ability to follow instructions and actively engage in the study. Together, these elements of the recruitment process ensured that only individuals with sufficient mental capacity were enrolled. As a result, no issues arose during the study related to participants being unable to understand instructions or complete the tasks.

4.2.4 Laboratory Setting

Motor function data has been collected in the Movement and Exercise Laboratory (MoveExLab) at the University of East Anglia. This facility was adapted to COVID-19 safety

guidelines. Biomechanical measurements were conducted using the same protocol and instrumentation with the second study, this protocol is explained in Chapter 3/Section 3.2.5., on page 91. Therefore, it is not detailed in this chapter. In addition to biomechanical measurements, the Fugl-Meyer Assessment tool for the lower extremities was used to assess motor function in this study. Sleep and mental health assessments were conducted in participants' homes after they received instructions in the MoveExLab. This approach was used to ensure data collection in a naturalistic environment for more accurate measurements.

To assess sleep, this study utilised subjective measurements, including the Pittsburgh Sleep Quality Inventory (PSQI) (Buysse *et al.*, 1989), and Karolinska Sleep Diary (KSD) (Åkerstedt *et al.*, 1994), while objective sleep data was collected using actigraphy (Cole *et al.*, 1992; Ancoli-Israel *et al.*, 2003). Mental health was assessed concurrently using the Brief Dimensional Apathy Scale (b-DAS) (Radakovic *et al.*, 2020), the Patient Health Questionnaire (PHQ-9) (Turner *et al.*, 2012), and the Generalised Anxiety Disorder assessment (GAD-7) (Spitzer *et al.*, 2006) to measure apathy, anxiety, and depression.

4.2.5 Instrumentation

4.2.5.1 Motor Function Assessment

4.2.5.1.1 Fugl-Meyer Assessment

The Fugl-Meyer Assessment (FMA) is a validated instrument mainly used to evaluate motor and sensory functions in patients recovering from a stroke (Fugl-Meyer *et al.*, 1975). The FMA lower extremity scale is provided in Appendix 15. FMA is a widely accepted tool in stroke rehabilitation research and clinical practice (Gladstone, Danells and Black, 2002). The assessment comprises six domains, each with a maximum score: Lower Extremity Motor Function (28), Coordination/Speed (6), Total Motor Function (34), Sensation (H) (12), Passive Joint Motion (I) (20), and Joint Pain (J) (20) (Fugl-Meyer *et al.*, 1975). These domains evaluate reflex activities, voluntary movements, synergy patterns, coordination, speed, sensory functions, range of motion in joints, and severity of pain experienced during passive movements (Fugl-Meyer *et al.*, 1975; Gladstone, Danells and Black, 2002).

4.2.5.2 Mental Health Assessments

Mental health questionnaires were used as confounding factors to explore the link between sleep and stroke recovery, grounded in the established correlation between sleep and mental health (Ong *et al.*, 2017).

4.2.5.2.1 Brief Dimensional Apathy Scale (b-DAS)

The Brief Dimensional Apathy Scale (b-DAS) is designed to evaluate different dimensions of apathy, a common feature in conditions that impact cognitive function or mental health, such as neurodegenerative diseases, brain injuries, or psychiatric disorders (Radakovic *et al.*, 2020), as provided in Appendix 10. The b-DAS examines three specific dimensions: executive, emotional, and behavioural apathy, and respondents use a Likert scale to rate the severity or frequency of their symptoms. The b-DAS is a recognised and validated screening tool with efficiency, reliability and validity levels in identifying apathy independent of physical disabilities The scoring system is between 0-27, with higher scores indicating worse apathy deficit (Radakovic *et al.*, 2020).

4.2.5.2.2 Patient Health Questionnaire (PHQ-9)

The Patient Health Questionnaire (PHQ-9), validated and recommended for use in stroke cases (Turner *et al.*, 2012), serves as an effective instrument for detecting depression (Appendix 13). The PHQ-9 employs a Likert scale to evaluate the frequency of depressive symptoms experienced over the preceding two weeks. The total score ranges from 0 to 27**,** with higher scores indicating more severe depressive symptoms (Kroenke, Spitzer and Williams, 2001).

The PHQ-9 includes a risk item that assesses suicidal ideation, which necessitates an appropriate response when endorsed. In this study, when a participant endorsed the PHQ-9 risk item, the approved ethical protocol was followed. With the necessary permissions in place, the participant's next of kin was contacted and advised to help the participant seek support from their general practitioner. This protocol was applied only once during the data collection.

4.2.5.2.3 The Generalised Anxiety Disorder Assessment (GAD-7)

The GAD-7 is a reliable and valid tool for measuring the severity of generalised anxiety symptoms (Spitzer *et al.*, 2006), as provided in Appendix 12. The GAD-7 comprises seven questions, each rated on a Likert scale to assess the level of anxiety experienced over the past two weeks. The total score ranges from 0 to 21, with specific thresholds used to categorise anxiety severity: 5-9 indicates mild anxiety, 10-14 moderate anxiety, and 15-21 severe anxiety (Spitzer *et al.*, 2006).

4.2.5.3 Sleep Measurements

4.2.5.3.1 Pittsburgh Sleep Quality Index (PSQI)

The Pittsburgh Sleep Quality Index (PSQI) is used to evaluate sleep quality and disturbances across a month (Buysse *et al.*, 1989). The full scale is provided in Appendix 11. The PSQI includes 19 items, forming seven component scores that assess various sleep aspects, which are sleep duration, disturbances, latency, efficiency, sleep quality, use of sleep medication, and daytime dysfunction. These components are measured through a combination of Likert scale responses and open-ended questions (Buysse et al., 1989). The total PSQI score ranges from 0 to 21, with higher scores indicating poorer sleep quality. Along with having multidimensional components, it is reliable and commonly used in research on sleep patterns and their impact on health (Buysse *et al.*, 1989).

The PSQI is its validated use in diverse populations, including stroke, showing good diagnostic sensitivity and specificity for sleep disorders (Palomäki *et al.*, 2003). The PSQI also shows high test-retest validity and reliability, especially in primary insomnia patients (Backhaus *et al.*, 2002). In this study, PSQI is employed to measure sleep quality in stroke participants, given its effectiveness in various groups.

4.2.5.3.2 Modified Karolinska Sleep Diary

The Karolinska Sleep Diary (KSD) is a validated subjective tool commonly used in sleep research to assess sleep duration, quality, disturbances, and daytime sleepiness (Åkerstedt et al., 1994). Similarly, the Consensus Sleep Diary (CSD) is a standardised sleep diary developed by a panel of sleep experts to provide a consistent and validated method for

capturing subjective sleep patterns, with wide application in both clinical and research settings (Carney et al., 2012).

In this study, a modified sleep diary was developed, drawing upon elements from both the KSD and CSD. The KSD was selected as a primary model due to its widespread use in human sleep research. However, the modified version integrates key components from the CSD, particularly in relation to questions on sleep and wake times. While the core structure is retained, there are some differences in wording compared to the original CSD.

The KSD places greater emphasis on detailed subjective assessments of sleep quality and disturbances. In contrast, many of these subjective components were omitted from the modified diary, as the broader subjective experience of sleep is addressed through other instruments used in the study. Instead, the modified diary focuses on essential sleep parameters, including sleep timing, duration, and night-time awakenings. Details of the sleep diary can be found in Appendix 14.

Regarding sleep quality, the modified version introduces a 1–9 Likert scale, differing from the scales used in both the KSD and CSD. This extended scale offers a more nuanced assessment of perceived sleep quality, allowing for greater sensitivity in detecting inter-individual differences.

Although some wording differences exist between the modified diary and the CSD, the modified version maintains alignment with the fundamental structure of both the KSD and CSD. To illustrate these similarities and distinctions, Table 4-1 presents a side-by-side comparison of the three tools.

Table 4-1 Comparing of CSD, KSD and Modified Questionnaire

Question	CSD	KSD	Modified Questionnaire
1. Time of Bedtime	What time did you get into bed?	Bedtime	What time did you go to bed?
2. Time of Trying to Sleep	What time did you try to go to sleep?	Not included	What time did you try starting to sleep at?
3. Time to Fall Asleep	How long did it take you to fall asleep?	Subjective sleep latency (hours and minutes)	How long did it take you to fall asleep? (min)
4. Number of Awakenings	How many times did you wake up?	Number of awakenings	How many times did you wake up?
5. Duration of Awakenings	How long did these awakenings last?	Number of awakenings/hours of sleep	How long were you awake for? (min)
6. Final Awakening Time	What time was your final awakening?	Slept throughout the time allotted [yes (5)-woke up much too early (l)]	What time did you wake up?
7. Time of Getting Up	What time did you get out of bed for the day?	What time did you get up?	What time did you get up?
10. Sleep Quality Rating	Very poor to very good scale	very well to very poorly (5 to 1 scale)	Best sleep ever to Worst sleep ever (1 to 9 scale)

In conclusion, while the modified questionnaire differs slightly in wording from both the KSD and CSD, it maintains essential similarities with both tools. The focus on sleep timing and quality aligns with the primary objectives of the KSD and CSD. Additionally, the inclusion of a more detailed sleep quality scale (1-9) enhances the precision of the assessment.

4.2.5.3.3 Actigraphy

Actigraphy offers a simpler alternative to polysomnography (PSG) for tracking sleep-wake rhythms, with high reliability (Ancoli-Israel *et al.*, 2003; Fekedulegn *et al.*, 2020). However, it may misinterpret inactivity as sleep, necessitating the use of subjective sleep diaries to enhance accuracy, particularly in cases of low-functioning hemiparesis and fragmented sleep (Laakso *et al.*, 2004; Fekedulegn *et al.*, 2020; Gottlieb *et al.*, 2021). Therefore, in this study, sleep diary was used with actigraphy.

The GENEActiv (Activinsights, Cambridge, United Kingdom) is a fully waterproof wrist-worn accelerometer used for actigraphy measurements. It has a memory capacity of 0.5GB, allowing data logging at frequencies ranging from 10 to 100Hz. Additionally, it is equipped with ambient light and temperature sensors. Its open-source analytics and software development kits facilitate customisation and integration into broader systems (Activinsights, 2024).

4.2.6 Data Collection

The data collection for this study was conducted over two sessions at the MoveExLab. The second session was held three months ± four weeks after the first visit. This schedule is designed to allow time for recovery changes in line with stroke recovery studies. At the beginning of their participation, individuals formally consented and underwent allergy screenings. They then provided information across three categories:

- Biomechanical data (consistent with the prior study)
- Evaluations related to mental health and sleep.
- The Fugl-Meyer Assessment focuses on lower-limb motor skills.

Additionally, participants supplied demographic details and stroke-specific information. Please see the Figure 4-1 below for data collection flow.

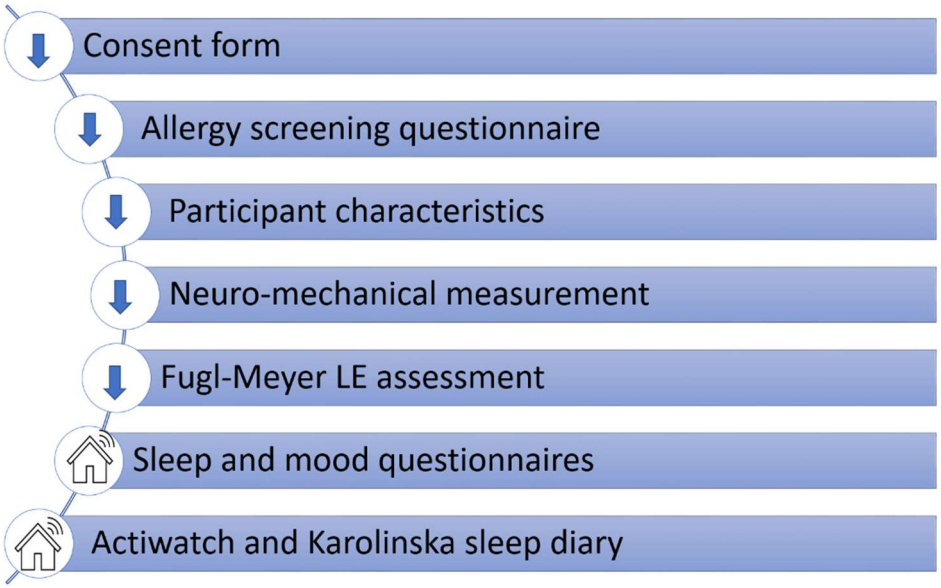


Figure 4-1 Trial design of sleep and stroke study

Further elaborating on the assessments, the first step involved collecting demographic data, including age, gender, and hand dominance, followed by stroke related clinical data, including which side of the body was most affected, the duration since the occurrence of the last stroke, and the total number of strokes.

The process for gathering biomechanical data replicated the approach of the second study, utilising Vicon motion capture technology. This phase also included taking anthropometric measurements as per Vicon's standardised recommendations. For a more detailed description, please refer to the methodology of the second study in Chapter 3, Section 3.2.6, on page 93. Following the biomechanical data collection, participants underwent the Fugl-Meyer Assessment to evaluate the motor function of their lower limbs.

In addition to these assessments, objective sleep data was obtained by equipping participants with GENEActiv devices for a continuous seven-day period. During this time, participants kept a sleep diary to record their sleep patterns at home. During this period, participants maintained a sleep diary to record their sleep patterns at home. Additionally, they were provided with a set of questionnaires to assess sleep quality and mental health, including the GAD-7, PHQ-9, b-DAS, and PSQI, which they completed at home.

The instructions for completing the home assessments were provided both verbally and in writing at the end of the lab session. Written instructions were presented to the participants, with copies given to them for reference. Please refer to Appendix 16 for the written instructions for using the actigraphy watches, and Appendix 17 for the general home assessment instructions.

In the verbal instructions, the written instructions were summarised, and participants were informed that they could refer to the documents for further details. They were asked if they understood the instructions and encouraged to ask any questions. Each assessment (questionnaire and diary) was then shown to the participants, and it was explained how to fill them out. They were reminded that the completed assessments should be returned by post at the end of the week. For the actigraphy watches, participants were informed that they did not need to press any buttons; the device automatically measures movement to estimate sleep time. They were instructed to wear it on their wrist for 7 days. They were also advised that, although the device is waterproof, it is best to remove it during showers and reattach it after drying off. Contact information was provided should they have any further questions.

The second session involved repeating all previously mentioned assessments except for the anthropometric measurements, as no significant changes were expected in these parameters over the short interval between the sessions.

In summary, biomechanical assessments were completed in the lab over two sessions, held 2-3 months apart. Sleep and mental health questionnaires were completed within one week and actigraphy watches were used in these 7 nights after the biomechanical assessments in these two sessions and returned to the researcher by post.

4.2.6.1 Trial Design

In this study, the biomechanical data collection procedures follow those established in the second study. The task started when participants were seated on an adjustable plinth, their feet resting on force plates, and a telephone positioned three meters ahead as the target. The plinth was adjusted to each participant's shank length, ensuring they were seated at a 90-degree angle at their hips, knees, and ankles. This posture provided support for the proximal half of their femurs. Participants were instructed to sit upright; their heads aligned directly above the pelvis. Stroke participants could support their affected arm by holding their elbow rather than keeping their hands by their side while awaiting the buzzer signal. The setup included one force plate under the plinth and two others under the participants' feet, allowing us to capture the force transformation during the transition in the sit-to-walk (STW) task.

Participants were tasked with answering the telephone upon hearing a buzzer. The instructions promoted natural movement, avoiding detailed instructions that could lead to unnatural or segmented motions. Participants practised the task before data collection until they felt comfortable with the procedure. The protocol involved completing five trials, each of which followed checking marker visibility and data quality. Stroke participants were encouraged to attempt the STW task five times, regardless of their ability to complete it successfully. Each attempt, successful or not, was recorded.

Additional safety measures were implemented to ensure the well-being of participants: A researcher was always near the participant throughout the task to monitor safety and provide immediate assistance. In cases where participants required additional support, a

stick or walker was made available at the end of each task. Furthermore, participants' comfort was consistently monitored by asking how they felt during the task and whether they needed a break.

The Fugl-Meyer Assessment was conducted following the biomechanical measurements. In cases where participants had restricted mobility, the Fugl-Meyer and anthropometric measurements that required the same position were performed together to avoid tiredness. Mental health assessments were conducted using questionnaires and actigraphs. Related questionnaires and GENEActiv devices for each wrist were given to participants at the end of the lab session if they could put on/off the devices by themselves or with the help of their career. Clear verbal and written instructions were given on how to use the actigraphs and fill out the questionnaires, and participants were encouraged to contact the researcher with any questions.

These assessments are recorded in patients' homes in the comfort of natural environments for seven consecutive days according to the recommendations (Aili *et al.*, 2017). After a week, participants were instructed to return these questionnaires and the GENEactiv watches using a provided prepaid envelope. All assessments were repeated in the second session except for the anthropometric measurements; the data collected during the first session remained.

Each trial session for stroke participants lasted around two hours**,** including the STW tests, Fugl-Meyer Assessment, sleep diary instructions, and mood questionnaire guidance. To minimise fatigue, participants were given rest breaks as needed. The second session was relatively shorter, as anthropometric measurements for the Vicon assessments were not repeated, reducing the overall testing time.

4.2.7 Data Processing

In this study, the biomechanical data processing approach followed the same protocol as the second study. Marker labelling and the creation of 3D marker trajectories were performed using Nexus 7 software. The process involved calibrating the system with a five-marker wand and applying biomechanical models, such as Plug-in Gait®. Data processing was conducted in several stages, including:

- Gap filling,
- Marker labelling,
- Establishing coordinate systems,
- Smoothing the data, and
- Exporting the data for further analysis in MATLAB

For more detailed information about these steps and the variables derived from Vicon system, please refer to Chapter 3, Section 3.2.7, page 98.

In addition to biomechanical data, sleep and mental health assessments were conducted in this study. The sleep data collected from the GENEActiv devices required processing using specialised software. Initially, the data in .bin file format were extracted using GENEactiv software. After consulting with GENEActiv for guidance on data processing, a software update was awaited to enable the conversion of .bin files to .awd files, as recommended by the company. This update enabled the use of Actiware 6 software for further analysis (Version 6.0.4, Philips Respironics, 2017), as it was compatible with .awd file type.

The steps for processing the actigraphy data were as follows:

- **Conversion of .bin files to .awd files:** The raw data was converted into a format suitable for analysis using GENEactiv Software and epochs were set to 30 seconds.
- **Importing to Actiware Software:** The .awd files were imported into the software for processing.
- **Analysis of sleep patterns:** Sleep patterns were analysed using two different methods: rest times were assigned either based on sleep diary data or according to activity patterns.
- **Calculation of sleep periods:** In the first method, the software automatically calculated sleep periods after rest times were assigned based on bedtime and wake-up times provided in the sleep diary. In the second method, sleep periods were automatically determined by the software algorithm based on activity patterns.
- **Data Verification:** In the first analysis method, automatically assigned sleep periods were compared to the sleep diary. If a significant discrepancy- more than 15

min- is detected between the sleep diary and actigraphy, the sleep diary is considered as primary source due to actigraphy's limitation of distinguishing low activity and sleep (Sadeh, 2011). This verification step was not applied in the second analysis method.

- **Data Exportation:** Once the data was processed, it was exported to Excel. Variables derived from the first analysis method were labelled as ACT-1, while those from the second method were labelled as ACT-2. Various sleep parameters were included in the Excel file for subsequent analysis using SPSS.

4.2.7.1 Sleep Variables

Sleep analysis was based on night sleep. Therefore, daytime naps were not included in the sleep analysis. The Philips Actiware-6 software was used to assess sleep. After processing the data, the software automatically calculates various sleep variables (Philips Respironics, 2023). Due to the extensive variety of the variables, the dataset was streamlined to align with research objectives which are to investigate the relationship between sleep duration and quality and their impact on stroke recovery outcomes.

A comprehensive set of variables derived from actigraphy was explored in the analysis:

Sleep duration: Time in bed (TIB) and Total sleep time (TST)

Sleep Continuity: Wake after sleep onset (WASO) and average wake bout duration (Avg Wake B), sleep onset latency (SOL), sleep efficiency (SE)

The explanations of sleep variables are as follows:

- **TIB (Time in Bed):** The total amount of time participants spent in bed. In actigraphy it is defined as the average duration, in minutes, between the start and end times of a given rest interval, representing the time spent in bed, at rest, or attempting to sleep (Philips Respironics, 2023).
- **SOL (Sleep Onset Latency):** The amount of time it took participants to fall asleep.
- **TST (Total Sleep Time):** The total duration of sleep during the night. In actigraphy analysis it is calculated as The total number of minutes within a given rest interval

that are scored as sleep by the sleep detection algorithm, representing the time during which sleep is occurring sleep (Philips Respironics, 2023).

- **SE (Sleep Efficiency):** The percentage of time in bed spent sleeping, calculated as (TST/TIB) * 100.
- **WASO (Wake After Sleep Onset):** The amount of time spent awake after initially falling asleep. In actigraphy analysis, it is defined as the total number of minutes scored as wakefulness within a given sleep interval.
- **Avg Sleep B:** The average length of the sleep bouts, calculated by dividing Actual Sleep Time by the Number of Wake Bouts.
- **TIB for Sleep:** The time starts from when the participant attempts to fall asleep after going to bed, as recorded in the sleep diary.
- **QOS (Quality of Sleep):** Assessed by the question "How was your quality of sleep?" and rated on a Likert scale from 1 to 9, with higher values indicating worse sleep.

Sleep onset latency derived from actigraphy measurements differed significantly between methods. In ACT-1 analysis, sleep diary entries were used for wake-up and sleep times, resulting in sleep onset latency values closely matching those in the sleep diary. However, in ACT-2 analysis, the actigraphy algorithm automatically determined sleep and wake-up times, as well as the sleep period. This algorithm was overly sensitive to activity, which may have resulted from using actigraphy devices from a different company than the one providing the software for data analysis. When activity levels dropped, it immediately identified this as the start of the sleep period, leading to unrealistically short sleep onset latency. Essentially, it assumed that the rest period and sleep itself began as soon as activity levels dropped. This situation results on unrealistically short sleep onset latency (SOL) values with mean 0.31 minutes. Therefore, SOL variable derived from ACT-2 analysis was not included the assessments.

Some of these actigraphy variables are shared with subjective sleep measurements: the common variables from the PSQI and sleep diary included time in bed (TIB), sleep onset latency (SOL), total sleep time (TST), and sleep efficiency (SE). Additionally, the sleep diary provided wake after sleep onset (WASO) as an extra variable. Further sleep quality indicators were also derived from these subjective assessments. These include:

Sleep Quality: PSQI global score, quality of sleep question which is based on responses to a morning questionnaire in the sleep diary, where participants rate their perceived sleep quality from the previous night.

4.2.8 Statistical Analysis

This study employed several statistical methods to analyse the relationships between sleep duration, continuity, quality, and motor function, with confounding factors including mental health, age, and gender. Normality tests were conducted as a prerequisite for subsequent parametric statistical analyses.

Pearson and Spearman correlation analyses were carried out to investigate the links between motor function and sleep indicators, aiming to understand the association between motor function and sleep quality. Following this analysis, the most correlated sleep variables with motor function were selected for general linear regression to identify which sleep variables are most strongly associated with motor function.

For linear analysis, Generalised Linear Model (GLM) was used due to it can handle outcome variables that do not follow a normal distribution which is important due to coordination 2 variable in Session 2 is not follow normal distribution. This test was conducted using three models: the first was an uncontrolled model, the second was a half-controlled model that adjusted only for age and gender, and the third was a fully controlled model that included mental health questionnaires—GAD-7, B-DAS, and PHQ-9—in addition to age and gender. This approach aimed to elucidate the details of the relationship between sleep and motor function and to determine which sleep variables are strongly correlated with motor function. The significance level for all these tests was set at 0.05.

4.3 Results

This section examines stroke recovery progress across two sessions, focusing on the research objectives. The first objective was to investigate the differences in sleep-related variables derived from objective and subjective assessments. To achieve this, sleep quality, duration, and continuity variables were collected through subjective and objective methods

where possible and subsequently analysed to identify potential discrepancies or complementary insights.

Additionally, the study aimed to the relationships between sleep variables and recovery metrics were investigated across the sessions. For this purpose, correlations between sleep parameters and motor function, as assessed by biomechanical analysis and the Fugl-Meyer Assessment, were assessed at two-time points.

The last objective was to identify the most strongly correlated sleep variables. This objective was accomplished through multivariate regression analysis, which accounted for demographic and mental health factors. These steps aimed to evaluate the interplay between sleep and motor function considering potential confounding factors.

4.3.1 Participant Recruitment and Demographics

This study aimed to recruit 54 patients, but due to the impact of COVID-19, only 45 were enrolled. One participant was excluded from the analysis after being retrospectively diagnosed. His stroke was only identified later through an MR scan. The researcher was informed about it during the first session, which led to incomplete baseline information. Consequently, 44 participants were included in the analysis. The group included 25 females and 19 males, aged 35 to 85, with an average age of 62.3 years. The time since their strokes was varied widely from 0.2 to 22 years, with an average duration of 6.7 years. Participants were mostly chronic stroke survivors, with only 5 individuals being within 6 months post-stroke.

A total of 44 people wore actigraphy watches, with 41 wearing them on both wrists. Three individuals wore only one actigraphy watch, on their affected hand, regardless of dominance due to impairments they were not able to take off both watches when needed.

Table 4-2 presents detailed demographic information for all participants. All enrolled individuals completed the initial data collection, although not everyone completed all the assessments due to their impairments. By the time of the follow-up session, the cohort had been reduced by 11.4% (5 participants). The reasons are listed as follows: two participants

were unresponsive to contact attempts, two experienced health issues, and one had another stroke.

Table 4-2 : Demographic and clinical characteristics of participants

Variable	Data (Mean ± SD, Range)
Participants (N)	44
Age (years)	62.3 ± 12.4, 35.0 - 85.0
Body Mass (kg)	79.9 ± 13.8, 54.3 - 106.0
Height (cm)	171.4 ± 7.1, 159.7 - 183.2
Time after Stroke (years)	5.7 ± 5.1, 0.2 - 22.0
Sex (N)	Male: 25, Female: 19
Dominant Side (N)	Right: 31, Left: 13
More Affected Side (N)	Right: 29, Left: 15

4.3.2 Data Collection and Analysis Challenges

4.3.2.1 Biomechanical Data Challenges

The data collection process encountered several technical challenges that impacted the usability of the gathered data. Therefore, the number of trials included in the statistical analysis varied. Common issues were visibility problems during data capture, incorrect foot placement during movement, and incompatibilities with extraction codes. These challenges are discussed in detail in Chapter 3, Section 3.3.2, page 103.

Incompatibilities with extraction codes mainly arose in the stroke group. Some participants could not complete the sit-to-walk task due to impairments, rendering their data incompatible with the extraction codes. Consequently, these participants were excluded; the rest represented a more homogeneous stroke severity in the study.

Details of data-related challenges included the exclusion of seven participants who used ankle-foot orthoses (AFOs), as these devices significantly altered gait biomechanics and interfered with consistent kinematic analysis. Additionally, nine participants were unable to complete the sit-to-walk task in session one, and six more were unable to do so across both sessions due to physical impairments. Although such limitations were anticipated, the STW task was purposefully selected for its suitability in capturing transitional movements and enabling EMG-based assessment of muscle reaction times. However, due to the large

number of outcome variables, EMG-derived metrics were ultimately excluded from the final analysis to maintain focus and interpretability.

Despite these obstacles, the study yielded 102 to 125 high-quality trials per variable across two sessions. The results from these quality trials for each kinematic metric are presented in Table 4-3. The range of trials per participant varied from 1 to 6 for all variables.

Table 4-3 Biomechanical analysis trial data

Variables	Session 1		Session 2	
	N/ Total Trials	$\bar{x}$ n trials	N / Total Trials	$\bar{x}$ n trials
Hesitation	29 / 125	4.24	24 / 104	4.25
Coordination 1	29 / 124	4.27	24 / 102	4.25
Coordination 2	29 / 124	4.31	24 / 103	4.29
Smoothness	30/ 125	4.31	24/ 104	4.33

Abbreviations: N= Number of Participants, $\bar{x}$ n trials = mean number of trials per subject

4.3.2.2 Sleep Measurement Challenges

The primary challenge in analysing sleep data arose from processing actigraphy data. This data required the integration of two distinct software platforms, which complicated the data process. The first step involved converting data files derived from GENEactiv watches to ensure compatibility with data analysis software (Philips Actiware). This process was time-consuming due to a delay in update the GENEactiv software that allows for file conversion.

The other challenge was that incomplete responses in questionnaires and sleep diaries led to an inability to calculate certain scores, resulting in data loss. These assessments were given to participants with GENEactiv watches at the end of the lab trials. Instructions on how to fill out these forms were provided to participants verbally. These instructions were also provided in written format, and the researchers' phone number was included in this document. If participants had questions or required additional help, they were informed that they could call this number. However, this approach did not resolve the issue of data loss from the questionnaires.

Sleep duration and continuity data were collected using both subjective and objective measurements. For objective data, actigraphy data was analysed using two methods: one based on sleep and wake times recorded in the sleep diary, and the other solely based on

light and activity data from the actigraphy, without reference to the sleep diary. The sleep diary and the Pittsburgh Sleep Quality Index (PSQI) were utilised for subjective measurements. The PSQI differs from the other tools as it focuses more on sleep habits over a one-month period. The data obtained from these various methods differed considerably, and the literature highlights the strength of using both methods. Therefore, it was decided to retain all sleep data sources and explore their associations with stroke recovery.

4.3.3 Descriptive Statistics of Sleep Duration and Continuity Variables Measured by Objective and Subjective Methods across the Two Sessions

Table 4-4 presents descriptive statistics of sleep measures. There are two different measurements of time in bed. The first measurement, which refer as TIB, begins when participants enter bed, while the second measurement, TIB for sleep, starts from the time participants intend to sleep. Both Actigraphy-1(ACT-1) and the sleep diary provide these TIB for Sleep measurements.

ACT-1 data were generated by aligning actigraphy-derived movement data with participant-reported sleep diary entries. This practice is widely recommended in sleep research, as it enhances accuracy and reduces errors associated with relying solely on algorithm-based estimations (Ancoli-Israel et al., 2015).

Recent technological developments, such as voice-interactive sleep logs and automated diary integration, have also demonstrated the advantages of combining subjective and objective measures. These combined approaches help improve the precision of sleep assessment (Lewin et al., 2024).

In line with these practices, ACT-1 used sleep diary entries to refine the timing of sleep onset and final awakening. Other parameters, such as wake after sleep onset (WASO), were calculated using the actigraphy algorithm alone. This was because movement-based systems are more sensitive in detecting brief nocturnal awakenings, such as getting up to use the bathroom, which are often not reported accurately. Participants may not recall these short or fragmented awakenings due to limitations in memory during the night.

In contrast, ACT-2 was entirely algorithm-driven, without any integration of sleep diary data. While previous studies have largely focused on comparing different actigraphy scoring algorithms (Kim et al., 2013; Gao et al., 2022; Liu et al., 2024), this study addressed a different comparison. It examined the differences between ACT-1 (algorithm combined with sleep diary) and ACT-2 (algorithm-only) approaches, to evaluate how each method relates to motor function outcomes.

Table 4-4 Descriptive statistics of sleep measurements

	Variables	ACT-1	ACT-2	PSQI	S. Diary
		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Session 1	TIB (min)		502.16(68.00)	529.55(66.94)	536.64 (67.50)
	SOL (min)	19.39 (21.14)		22.73(24.59)	19.40 (21.51)
	TST (min)	235.50 (114.81)	250.95(129.79)	427.56(78.98)	401.54 (114.17)
	SE (%)	46.26 (21.59)	51.15(25.68)	80.73(12.45)	78.47 (17.34)
	WASO (min)	198.71 (123.13)	237.38(125.86)		31.75 (46.18)
	Avg Sleep B (min)	40.40 (40.76)	34.02(32.70)		
	TIB for Sleep (min)	444.79 (73.29)			437.30 (84.47)
Session 2	TIB (min)		503.73 (61.7)	533.48 (62.76)	537.16 (61.59)
	SOL (min)	13.52 (19.12)		20.23 (22.32)	13.76 (13.35)
	TST (min)	238.68 (112.17)	259.15 (127.99)	441.49(62.50)	443.18 (64.13)
	SE (%)	45.94 (22.85)	52.37 (26.10)	82.14 (11.20)	83.98 (9.76)
	WASO (min)	219.05 (129.18)	236.99 (131.42)		18.77 (21.49)
	Avg Sleep B (min)	43.74 (76.12)	44.93 (75.84)		
	TIB for Sleep (min)	463.52 (66.55)			459.15 (64.61)

TIB (Time in Bed), SOL (Sleep Onset Latency), TST (Total Sleep Time), SE (Sleep Efficiency), WASO (Wake After Sleep Onset), Avg Sleep B: The average sleep bouts, TIB for Sleep: The time starts when the participant tries to fall asleep after going to bed, S. diary: Sleep Diary, PSQI: The Pittsburgh Sleep Quality Index, ACT-1: Actigraphy data processed based on sleep and wake times recorded in the sleep diary, ACT-2: Actigraphy data that is processed solely based on light and activity data from the actigraphy

Session 1 (S1) Results (Table 4-4):

- **TIB**: The time in bed varies across methods, with actigraphy (ACT-1, ACT-2) showing lower TIB than subjective measurements (PSQI, Sleep Diary), in ACT-2 (502.16 min) compared to the Sleep Diary (536.64 min). ACT-1 using TIB for sleep, therefore, it is shorter than other assessments (444.79 min).
- **Sleep Onset Latency (SOL):** SOL values were consistent across actigraphy, PSQI and sleep diary.

- **Total Sleep Time (TST):** Actigraphy estimates significantly lower total sleep time, with ACT-1 recording 235.50 minutes and ACT-2 recording 250.95 minutes. In contrast, subjective measures such as the PSQI report 427.56 minutes and the Sleep Diary report 401.54 minutes.
- **Sleep Efficiency (SE):** Sleep efficiency follows a similar trend, with lower efficiency rates recorded by actigraphy (46.26% for ACT-1 and 51.15% for ACT-2) compared to subjective measures (PSQI: 80.73%, Sleep Diary: 78.47%).
- **WASO**: Actigraphy suggests considerable wakefulness after sleep onset (ACT-1: 198.71 min, ACT-2: 237.38 min), which is not recorded in subjective methods.
- **Avg Sleep B**: This variable shows less variability between actigraphy assessments.

Session 2 (S2) Results (Table 4-4):

- **TIB**: Time in bed is more consistent across sessions, though similar patterns of difference are observed between actigraphy (lower TIB) and subjective tools (higher TIB).
- **SOL**: PSQI reported slightly higher values than actigraphy and sleep diary
- **TST**: As with Session 1, actigraphy underestimates total sleep time compared to subjective measures. PSQI and the sleep diary report around 440+ min, while actigraphy estimates are below 260 min.
- **SE**: Sleep efficiency improves slightly in Session 2 but follows the same trend, with actigraphy reporting much lower efficiency than subjective measures.
- **WASO**: Time spent awake after sleep onset remains high in actigraphy, while the sleep diary reports much lower values in both sessions (S1: 31.75 min, S2: 18.77 min).
- **Avg Sleep B**: According to both actigraphy assessments, there is a slight increase in session 2

In summary, the table highlights significant discrepancies between objective (actigraphy) and subjective (PSQI, sleep diary) sleep measures. Actigraphy tends to report considerably lower total sleep time, sleep efficiency, and higher wakefulness, while subjective measures reflect longer sleep duration and higher sleep efficiency. The close match between actigraphy-1 and the sleep diary in SOL and TIB for Sleep variables is due to the use of sleep diary data. In actigraphy-1, sleep and wake-up times are based on the information provided in the sleep diary.

4.3.4 Descriptive Statistics of Subjective Sleep and Mental Health Variables and Biomechanical Metrics Across Sessions

This section reports the descriptive statistics of variables measured across the two assessment sessions. These statistics illustrate the range and distribution of variables, providing a foundation for subsequent analyses. Detailed data for these variables are presented in Table 4-5.

Table 4-5 Descriptive statistics of motor function, mental health and sleep quality variables

Variables	Session 1		Session 2	
	N\44	Mean (Std. Deviation)	N\39	Mean (Std. Deviation)
Mental Health Scores				
GAD-7	41	4.46 (5.16)	36	4.47 (5.20)
PHQ-9	40	6.17 (6.14)	35	5.66 (5.59)
BDAS	34	10.94 (3.84)	33	10.39 (3.95)
Motor Function Metrics				
Hesitation	29	45.45 (19.80)	24	43.12 (19.34)
Coordination1	29	16.42 (7.41)	24	13.57 (7.67)
Coordination2	29	-5.39 (2.46)	24	-5.68 (2.57)
Smoothness	30	-2.28 (0.28)	24	-2.25 (0.29)
FMA-LL	41	28.07 (7.82)	37	28.65 (7.14)
Sleep Quality Measurements				
PSQI global score	35	6.54 (3.45)	34	6.32 (3.42)
Quality of sleep	42	3.87 (1.28)	39	3.73 (1.45)

GAD-7: Generalized Anxiety Disorder-7, PHQ-9: Patient Health Questionnaire: Brief Disability Assessment Scale, BDAS: Brief Dimensional Apathy Scale, FMA-LL: Fugl-Meyer Assessment-Lower Limb, PSQI Global Score: Total score of the Pittsburgh Sleep Quality Index

There were 44 participants in session 1 and with lost follow up the max number of participants in second session 39. As shown in Table 4-5, missing data were observed across mental health and sleep assessments in both sessions. In Session 1, GAD-7 had 7% missing data, which increased to 8% in Session 2. Similarly, PHQ-9 had 9% missing data in Session 1 and 10% in Session 2. BDAS showed the highest percentage of missing data among the mental health measures, with 23% in Session 1 and 15% in Session 2. For sleep assessments, PSQI global scores had 20.45% missing data in Session 1 and 13% in Session

2, while the quality of sleep measure had 5% missing data in Session 1 but was fully reported in Session 2."

In the domain of mental health, scores remained relatively stable across sessions. For instance, Generalized Anxiety Disorder-7 (GAD-7) scores had a mean of 4.46 (SD = 5.16) in Session 1 and 4.47 (SD = 5.20) in Session 2.

Regarding Sleep Metrics**,** the Pittsburgh Sleep Quality Index (PSQI) mean scores were relatively consistent in sessions, with mean scores of 6.54 (SD = 3.45) in Session 1 and 6.32 (SD = 3.42) in Session 2. The quality of sleep, evaluated through a direct question in the sleep diary where participants rated their own sleep quality, remained stable across both sessions.

4.3.5 Normality Testing and Outlier Analysis

The following variables were identified as not following a normal distribution-based Shapiro-Wilk test ($p<0.05$) and are recommended for non-parametric tests:

In Session 1, the variables included ACT-1 average sleep bout (Avg Sleep B), ACT-1 Sleep Efficiency (SE), ACT-1 total sleep Time (TST), ACT-2 sleep efficiency (SE), ACT-2 Total Sleep Time (TST), average sleep bout (Avg Sleep B), Fugl-Meyer Assessment for Lower Limbs (FMA-LL), Generalised Anxiety Disorder-7 (GAD-7), Patient Health Questionnaire-9 (PHQ-9), sleep onset latency derived from Pittsburgh Sleep Quality Index (SOL), quality of sleep (QOS), sleep onset latency from sleep diary (SOL), and wake after sleep onset from sleep diary (WASO).

For Session 2, the variables were ACT-1 average sleep bout (Avg Sleep B), ACT-1 sleep onset latency (SOL), ACT-2 average sleep bout (Avg Sleep B), ACT-2 wake after sleep Onset (WASO), Fugl-Meyer Assessment for Lower Limbs (FMA-LL), Patient Health Questionnaire-9 (PHQ-9), sleep efficiency from Pittsburgh Sleep Quality Index (SE), sleep onset latency from sleep diary (SOL), wake after sleep onset from sleep diary (WASO) and coordination 2. This structured approach to preliminary data testing ensures that the statistical methods applied in further analyses match the data characteristics.

4.3.6 Comparison of motor function Variables Between Two Sessions

The Table 4-6 presents the results of statistical tests used to assess motor function progress between two sessions.

Table 4-6 Comparison of motor function variables between two sessions

Test	Variables	p-value
Paired t-Test	Hesitation	0.007*
	coordination 1	0.27
	Smoothness	0.062
Wilcoxon Signed-Rank Test	FMA-LE	0.377
	Coordination 2	0.485

*Significant result
FMA-LE: Fugl-Meyer Assessment for Lower Extremity

To assess motor function progress, the paired t-test was utilised to identify significant differences between the two sessions for variables conforming to a normal distribution. The 'hesitation' metric showed a significant shift ($p = 0.007$), indicating that this fluency metric was improved between sessions. The Wilcoxon Signed-Rank Test was used for variables that did not follow a normal distribution, and no significant session-to-session differences were found.

4.3.7 Investigation of Relationships between Biomechanical Variables and Sleep Assessments

This analysis investigate the correlations between motor function variables and several dimensions of sleep, to understand their relationship. Depending on the normalisation of the data, both Pearson and Spearman correlation approaches were used, and significant connections across numerous metrics, as shown in **Error! Reference source not found.** and **Error! Reference source not found.**. Due to the extensive volume of data, objective and subjective sleep assessments were presented separately.

For correlations between the FMA and sleep metrics, the sample size (N) ranged from 29 to 41 in Session 1 and from 29 to 36 in Session 2—the highest among motor function variables. Correlation sample sizes for Actigraphy measures (ACT-1 and ACT-2) varied between 26 and

29 in Session 1 but dropped to 17-18 in Session 2. The same numbers from subjective sleep measurements are: In Session 2, correlation sample sizes (N) for subjective sleep assessments and fluency metrics range between 21 and 24. In Session 1, sample sizes are slightly higher, ranging between 24 and 29 for sleep metrics derived from the sleep diary and the PSQI, except for PSQI TIB, which has an N of 22.

Table 4-7 Pearson and Spearman Correlations between sleep and motor function variables in Session 1

		PSQI					ACT-1						ACT-2					S. DIARY						
		GL. S.	TIB	SOL	TST	SE	TIB	SOL	SE	WASO	TST	Avg. S. B	TIB	SE	WASO	TST	Avg. S. B	WASO	SOL	TIB	TIB FOR S.	TST	SE	Q0S
FMA-LE	r	-0.30	-0.19	-0.18	0.05	0.21	-0.04	-0.27	-0.17	0.25	-0.25	-0.15	0.06	-0.20	0.24	-0.18	-0.08	0.14	-0.20	-0.39*	0.06	-0.07	0.14	-0.07
	p	0.10	0.33	0.30	0.77	0.23	0.82	0.10	0.30	0.14	0.13	0.36	0.69	0.22	0.13	0.27	0.61	0.38	0.21	0.01	0.70	0.67	0.43	0.69
HES	r	0.28	0.28	0.19	-0.09	-0.27	0.36	0.15	-0.21	0.29	-0.18	-0.39*	0.21	-0.13	0.14	-0.10	-0.37*	0.24	0.31	0.29	0.19	0.22	0.09	0.53**
	p	0.18	0.20	0.36	0.66	0.18	0.07	0.47	0.30	0.15	0.37	0.05	0.28	0.49	0.47	0.60	0.05	0.22	0.11	0.13	0.34	0.26	0.67	0.00
C1	r	0.24	-0.08	0.09	-0.14	0.03	-0.39	-0.10	0.26	-0.45*	0.20	0.41*	-0.41*	0.19	-0.33	0.11	0.34	-0.04	-0.09	-0.35	-0.44*	-0.42*	-0.39	-0.08
	p	0.26	0.73	0.66	0.50	0.89	0.05	0.61	0.19	0.02	0.32	0.04	0.03	0.33	0.08	0.58	0.07	0.85	0.66	0.07	0.02	0.03	0.06	0.69
C2	r	-0.17	0.16	-0.03	0.26	0.12	0.36	-0.31	0.03	0.10	0.07	-0.04	0.27	0.12	-0.07	0.14	-0.02	-0.04	-0.13	0.31	0.40*	0.46*	0.19	0.00
	p	0.43	0.47	0.89	0.20	0.57	0.07	0.13	0.89	0.61	0.75	0.84	0.16	0.52	0.73	0.48	0.92	0.86	0.52	0.10	0.03	0.01	0.38	1.00
SMO	r	-0.28	-0.38	-0.27	0.09	0.32	-0.30	-0.13	0.13	-0.19	0.10	0.27	-0.13	0.06	-0.04	0.03	0.26	-0.19	-0.32	-0.22	-0.15	-0.21	-0.08	-0.44*
	p	0.19	0.08	0.18	0.66	0.11	0.13	0.51	0.50	0.33	0.62	0.17	0.49	0.73	0.85	0.90	0.16	0.33	0.09	0.26	0.43	0.29	0.70	0.02

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

The orange-coloured values were obtained using Spearman's correlation, p: p-value, r: correlation coefficient.

PSQI: Pittsburgh Sleep Quality Index, ACT-1: Actigraphy 1, ACT-2: Actigraphy 2, S. DIARY: Sleep Diary, GL. S.: Global Score, TIB: Time in Bed, SOL: Sleep Onset Latency, TST: Total Sleep Time, SE: Sleep Efficiency, WASO: Wake After Sleep Onset, Avg. S. B.: Average Sleep Bouts, TIB for S.: Time in Bed for Sleep, QOS: Quality of Sleep, FMA-LE: Functional Movement Assessment – Lower Extremity, HES: Hesitation, C1: Coordination 1, C2: Coordination 2, SMO: Smoothness.

Correlation between motor function and objective sleep assessment variables (ACT-1 and ACT-2) in Session 1 (Table 4-7)

- **Coordination-1** has a negative correlation with WASO (r = -0.45, p = 0.02) from ACT-1, suggesting that more wakefulness after sleep onset is associated with poorer coordination. Additionally, there is a negative correlation between Coordination-1 and TIB (r = -0.41, p = 0.03) from ACT-2, meaning more time in bed correlates with worse coordination. Coordination-1 positively correlates with average sleep bouts (Avg Sleep B) (r = 0.41, p = 0.04) from ACT-1, suggesting that longer sleep episodes are linked to better coordination.

  Hesitation is negatively correlated with Average sleep bouts derived from actigraphy-1 (r = -0.39, p = 0.05) and actigraphy-2 (r = -0.37, p = 0.05), implying longer sleep episodes are linked to reduced hesitation, better motor performance.

Correlation between motor function and subjective sleep assessment variables (PSQI and Sleep diary) in Session 1 (Table 4-7)

- **Coordination-1** shows a negative correlation with TST (r = -0.42, p = 0.03) and TIB for Sleep (r = -0.44, p = 0.02) from sleep diary, suggesting that increased total sleep time and time in bed are associated with poorer coordination performance. However, **Coordination-2** displays a positive correlation with TST (r = 0.46, p = 0.01) and TIB (r = 0.40, p = 0.03) from sleep diary, meaning longer sleep related to worse coordination-2, since coordination-2 values are negative due to direction of the movement.
- **Hesitation** is positively correlated with QOS (r = 0.53, p = 0.00) from sleep diary, indicating that lower subjective quality of sleep is linked to more hesitation in motor performance, which indicates less function.
- **Smoothness** shows a negative correlation with QOS (r = -0.44, p = 0.02) from sleep diary, implying that better sleep quality results in smoother movements.

In Addition, in Session 1, the FMA showed a significant correlation with the time in bed (TIB) variable derived from the sleep diary (r = -0.39, p = 0.01), which means more time in bed is correlated with less recovery rates measured by FMA.

Table 4-8 Pearson and Spearman Correlations between sleep and motor function variables in Session 2

		ACT-2					ACT-1						PSQI					S. DIARY						
		TIB	SE	WASO	TST	Avg. S.B	TIB	SOL	SE	WASO	TST	Avg. S. B	GLO.S.	TIB	SOL	TST	SE	WASO	SOL	TIB	TIB for S.	TST	SE	Q0S
FMA-LE	r	0.06	-0.06	0.13	-0.03	-0.01	0.00	-0.01	0.03	0.03	-0.06	0.00	0.00	-0.19	-0.06	0.04	0.23	-0.04	0.07	-0.26	-0.14	-0.15	0.06	0.10
	p	0.75	0.75	0.51	0.87	0.94	0.99	0.95	0.89	0.86	0.74	0.99	0.99	0.27	0.73	0.80	0.20	0.80	0.68	0.13	0.42	0.38	0.75	0.56
HES	r	-0.57*	-0.06	0.04	-0.19	-0.06	-0.42	-0.49*	-0.16	0.02	-0.24	0.13	0.62**	0.05	0.46*	-0.28	-0.23	0.11	0.37	0.16	-0.09	-0.09	-0.42*	0.36
	p	0.02	0.82	0.87	0.47	0.83	0.08	0.04	0.53	0.94	0.35	0.62	0.00	0.80	0.02	0.19	0.29	0.60	0.08	0.48	0.70	0.68	0.05	0.09
C1	r	0.13	-0.46	0.39	-0.39	-0.52*	0.16	0.26	-0.43	0.48*	-0.38	-0.61**	-0.58**	-0.16	-0.46*	0.48*	0.48*	-0.13	-0.35	-0.21	-0.04	0.02	0.43*	0.20
	p	0.62	0.06	0.13	0.12	0.03	0.52	0.29	0.07	0.04	0.12	0.01	0.01	0.46	0.03	0.02	0.02	0.56	0.09	0.34	0.84	0.93	0.04	0.34
C2	r	0.09	0.15	-0.15	0.16	0.14	0.22	-0.05	0.12	-0.12	0.16	0.11	0.41	0.30	0.20	0.18	-0.10	0.08	0.24	0.25	0.19	0.16	-0.15	0.55**
	p	0.72	0.55	0.56	0.54	0.60	0.38	0.84	0.64	0.64	0.53	0.67	0.07	0.16	0.34	0.41	0.64	0.71	0.26	0.25	0.37	0.47	0.49	0.01
SMO	r	0.60*	0.06	0.02	0.19	0.06	0.40	0.36	0.15	-0.01	0.21	-0.09	-0.64**	-0.10	-0.59**	0.34	0.33	-0.11	-0.44*	-0.13	0.09	0.12	0.54*	-0.32
	p	0.01	0.83	0.93	0.47	0.82	0.10	0.14	0.56	0.98	0.39	0.72	0.00	0.63	0.00	0.11	0.12	0.61	0.03	0.56	0.69	0.60	0.01	0.12

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

The orange-coloured values were obtained using Spearman's correlation, p: p-value, r: correlation coefficient.

PSQI: Pittsburgh Sleep Quality Index, ACT-1: Actigraphy 1, ACT-2: Actigraphy 2, S. DIARY: Sleep Diary, GL. S.: Global Score, TIB: Time in Bed, SOL: Sleep Onset Latency, TST: Total Sleep Time, SE: Sleep Efficiency, WASO: Wake After Sleep Onset, Avg. S. B.: Average Sleep Bouts, TIB for S.: Time in Bed for Sleep, QOS: Quality of Sleep, FMA-LE: Functional Movement Assessment – Lower Extremity, HES: Hesitation, C1: Coordination 1, C2: Coordination 2, SMO: Smoothness.

Correlation between motor function and subjective sleep assessment variables (PSQI and Sleep diary) in Session 2 (Table 4-8)

- **Coordination-1** shows a significant positive correlation with PSQI-derived total sleep time (r = 0.48, p = 0.02) and Sleep efficiency (r = 0.48, p = 0.02), suggesting that higher sleep efficiency and total sleep time are associated with better coordination performance. However, it has a negative correlation with the PSQI Global Score (r = -0.58, p = 0.01), meaning that better sleep performance from PSQI scores is linked to better coordination. It also shows a significant negative correlation with SOL from the PSQI (r = –0.46, p = 0.03), suggesting better coordination is associated with shorter sleep latency.
- **Coordination-2** exhibits a negative correlation with QOS (r = -0.55, p = 0.01), paradoxically indicating that better subjective sleep quality is related to worse coordination.
- **Hesitation** is negatively correlated with sleep efficiency (SE) (r = -0.42, p = 0.05) from sleep diary, suggesting that higher sleep efficiency is associated with reduced hesitation, better movement performance. It also shows a positive correlation with the PSQI Global Score (r = 0.62, p = 0.00), indicating that a better sleep score from PSQI is linked to reduced hesitation. It also shows a significant correlation with SOL on the PSQI (r = 0.46, p = 0.02), suggesting less hesitation (better quality of movement) is associated with shorter sleep latency.
- **Smoothness** is negatively correlated with SOL in both derived from sleep diary (-0.44, 0.03) and PSQI (-0.59, 0.00) meaning shorter sleep onset latency is associated with smoother movements. Additionally, Smoothness is positively correlated with sleep efficiency from the sleep diary (r = 0.54, p = 0.01), suggesting that higher sleep efficiency results in smoother motor performance. Smoothness negatively correlates with the PSQI Global Score (r = -0.64, p = 0.00), indicating that better sleep performance is linked to smoother movements.

Correlation between motor function and objective sleep assessment variables (ACT-1 and ACT-2) in Session 2 (Table 4-8)

- **Coordination-1** is positively correlated with WASO (r = 0.48, p = 0.04) in ACT-1, paradoxically suggesting that more wakefulness after sleep onset is linked to better coordination. Moreover, it shows a moderate negative correlation with average sleep B from ACT-1 (r = -0.61, p = 0.01) and from ACT -2 (r = -0.52, p = 0.03), indicating that longer sleep bouts are associated with worse coordination.
- **Hesitation** shows a negative correlation with SOL (r = -0.49, p = 0.04) in ACT-1, meaning a shorter time to fall asleep is associated with increased hesitation. There is also a moderate negative correlation between Hesitation and TIB (r = -0.57, p = 0.02) in ACT-2, suggesting that more time in bed reduces hesitation.
- **Smoothness** is positively correlated with TIB (r = 0.60, p = 0.01) in ACT-2, indicating that longer time in bed contributes to smoother motor performance.

4.3.8 Multivariate Regression Analysis for Understanding the Relationship between Multiple Measures of Sleep

Several sleep measures showed significant associations with motor function variables across both sessions. To construct a robust multivariate regression model, predictors that were statistically significant, conceptually relevant, and minimally correlated were selected to reduce the risk of multicollinearity.

Selected Variables for Regression Analysis:

1. **PSQI Global Score:** This measure consistently demonstrated significant correlations with motor function variables, including Coordination-1, Hesitation, and Smoothness in session 2, making it a strong predictor.
2. **Average Sleep B. (ACT-1):** This variable showed significant correlations with Coordination-1 and Hesitation across sessions.
3. **Time in Bed (TIB, ACT-2):** TIB was significant in both sessions for Coordination-1 and in the first session with Hesitation.
4. **Sleep Efficiency (SE, Sleep Diary):** Though not consistently significant across both sessions, it was included due to its moderate significance in Session 2, particularly for Coordination-1, Hesitation and Smoothness.
5. **Quality of Sleep (QOS):** This variable was constantly correlated with motor function variables in both sessions.

For linear analysis, the generalised linear model (GLM) is used because it can handle outcome variables that do not follow a normal distribution. This is important because the coordination2 variable in Session 2 does not follow a normal distribution. For this variable, log link function is used, due to only positive values are suitable for this model. Therefore, absolute values were taken for coordination 2 variable (Session 2). This step did not interfere with significant values, but it changed the direction of correlation. For rest of the dependent variables identity link function is used which is suitable for negative and positive values.

In the first step, the variables are not controlled. In the second step, which is called half-controlled, only age and gender are controlled. The third step is the fully controlled model, and mental health assessments (GAD-7, PHQ-8, and B-DAS) are added as controlled variables. Significant results are highlighted (Table 4-9).

Table 4-9 Linear regression analysis of correlated sleep variables with motor function across two sessions

		GLM - Uncontrolled Model					GLM - Half-controlled Model					GLM - Fully Controlled Model				
	Variables	**QOS-S.diary**	**SE-S.diary**	**TIB-ACT**	**PSQI-Global S.**	**Avg. Sleep B- ACT**	**QOS-S.Diary**	**SE-S.diary**	**TIB- ACT**	**PSQI-Global S.**	**Avg. Sleep B -ACT**	**QOS-S.Diary**	**SE-S.diary**	**TIB- ACT**	**PSQI-Global S.**	**Avg. Sleep B -ACT**
S1	**Coordination-1**	(B = -0.458, p = 0.785)	(B = -0.307, p = 0.129)	(B = -0.053, p = 0.029)*	(B = 0.161, p = 0.810)	(B = 0.061, p = 0.029)*	(B = -0.716, p = 0.688)	(B = -0.181, p = 0.409)	(B = -0.043, p = 0.082)	(B = 0.061, p = 0.926)	(B = 0.060, p = 0.022)*	(B = -1.590, p = 0.170)	(B = -0.524, p < 0.001)*	(B = -0.015, p = 0.317)	(B = -1.544, p = 0.007)*	(B = 0.046, p = 0.003)*
	Coordination-2	(B = 0.331, p = 0.606)*	(B = 0.052, p = 0.499)	(B = 0.013, p = 0.164)	(B = -0.105, p = 0.583)	(B = -0.012, p = 0.262)	(B = 0.241, p = 0.737)	(B = 0.055, p = 0.533)	(B = 0.013, p = 0.183)	(B = -0.083, p = 0.753)	(B = -0.012, p = 0.260)	(B = -0.121, p = 0.881)	(B = 0.006, p = 0.952)	(B = 0.017, p = 0.107)	(B = -0.073, p = 0.855)	(B = -0.014, p = 0.190)
	Hesitation	(B = 9.649, p = 0.002)*	(B = -0.390, p = 0.306)	(B = 0.035, p = 0.446)	(B = 0.630, p = 0.618)	(B = -0.097, p = 0.062)	(B = 9.889, p = 0.005)*	(B = -0.328, p = 0.444)	(B = 0.040, p = 0.408)	(B = 0.481, p = 0.709)	(B = -0.097, p = 0.059)	(B = 12.505, p < 0.001)*	(B = -0.145, p = 0.641)	(B = 0.062, p = 0.065)	(B = 0.434, p = 0.733)	(B = -0.110, p = 0.001)*
	Smoothness	(B = -0.132, p = 0.004)*	(B = 0.009, p = 0.087)	(B = 0.00, p = 0.702)	(B = -0.008, p = 0.670)	(B = 0.001, p = 0.241)	(B =-0.118, p = 0.017)*	(B = 0.009, p = 0.122)	(B = 0.000, p = 0.719)	(B = -0.012, p = 0.526)	(B = 0.001, p = 0.230)	(B = -0.174, p < 0.001)*	(B = 0.007, p = 0.091)	(B = -0.001, p = 0.234)	(B = 0.005, p = 0.766)	(B = 0.001, p = 0.024)*
S2	**Coordination-1**	(B = 3.667, p < 0.001)*	(B = 0.289, p = 0.033)*	(B = -0.031, p = 0.052)	(B = -2.107, p < 0.001)*	(B = -0.016, p = 0.073)	(B = 3.392, p < 0.001)*	(B = 0.271, p = 0.004)*	(B = -0.036, p = 0.002)*	(B = -1.862, p < 0.001)*	(B = -0.004, p = 0.551)	(B = 4.056, p =0.000)*	(B = 0.460, p <0.001)*	(B = 0.001, p = 0.910)	(B = 0.130, p = 0.696)	(B = 0.011, p = 0.003)*
	Coordination-2	(B = -0.206, p =0.002)*	(B = -0.006, p = 0.555)	(B = -0.001, p = 0.260)	(B = -0.037, p = 0.214)	(B = 0.000, p = 0.689)	(B = -0.101, p =0.019)	(B = 0.008, p = 0.236)	(B = -0.001, p = 0.074)	(B = -0.023, p = 0.216)	(B < 0.001, p = 0.970)	(B = -0.005, p =0.811)	(B = 0.035, p =0.000)*	(B = 0.001, p <0.001)*	(B = 0.127, p <0.001)*	(B = 0.001, p <0.001)*
	Hesitation	(B = 1.910, p = 0.620)	(B = 0.254, p = 0.685)	(B = -0.178, p = 0.016)*	(B = 3.223, p = 0.082)	(B = 0.020, p = 0.638)	(B = 1.995, p = 0.584)	(B = 0.368, p = 0.535)	(B = -0.208, p = 0.005)*	(B = 3.830, p = 0.039)*	(B = 0.020, p = 0.654)	(B = -2.647, p = 0.483)	(B = -0.775, p = 0.295)	(B = -0.307, p <0.001)*	(B = -2.816, p = 0.349)	(B = -0.022, p = 0.496)
	Smoothness	(B =-0.030, p = 0.580)	(B = -0.004, p = 0.673)	(B = 0.003, p = 0.005)*	(B = -0.050, p = 0.054)	(B = 0.000, p = 0.746)	(B = -0.032, p = 0.543)	(B = -0.005, p = 0.565)	(B = 0.003, p = 0.003)*	(B = -0.055, p = 0.040)*	(B = 0.000, p = 0.830)	(B = 0.041, p = 0.453)	(B = 0.014, p = 0.179)	(B = 0.005, p <0.001)*	(B = 0.065, p = 0.137)	(B = 0.001, p = 0.221)

*Highlighted Significant results,

TIB (Time in Bed): The total time participants spent in bed derived from actigraphy-2 analysis. Avg. Sleep B.: The average sleep bouts derived from actigraphy 1, SE (Sleep Efficiency): The percentage of time in bed spent sleeping (TST/TIB) derived from the sleep diary. S. diary: Sleep Diary, PSQI Global S: The Pittsburgh Sleep Quality Index Global Score, QOS: Assessed by a question "How was your quality of sleep?" and rated on a Likert scale from 1 to 9, higher values as worse sleep. ACT: Actigraphy, S1: Session 1, S2: Session 2, GLM: Generalised Linear Model. The half-controlled model controlled for age and gender. The fully controlled model adds mental health assessments (GAD-7, PHQ-8 and B-DAS) as controlled variables.

Coordination-1 (Table 4-9**)**

In session 1, Average sleep bouts remained a significant correlation with coordination-1 in all models. In a full-controlled model, sleep efficiency and PSQI were also negative but significantly correlated with coordination-1, which means paradoxically, increased sleep efficiency correlated with decreased coordination. However, better sleep quality (PSQI) and longer sleep bouts mean increased coordination. PSQI was the strongest predictor of coordination-1; for each one-unit increase in the PSQI, "Coordination-1" decreased by 1.544 units.

However, in session 2, average sleep bouts were only significantly correlated with coordination-1 in a fully controlled model. Instead, the quality of sleep remained significant in all models. In the fully controlled model, the coefficient for quality of sleep was 4.056, indicating that for each one-unit increase in sleep quality, coordination improved by approximately 4.056 units. Sleep efficiency also emerged as a significant predictor, with a coefficient of 0.460 ($p < 0.001$).

Coordination-2 (Table 4-9**)**

In session 1, coordination-2 was not significantly correlated with any of the sleep variables. However, in session 2, it was significantly and positively correlated with all the sleep variables except quality of sleep from sleep diary. However, the predictive powers of these were low.

Hesitation (Table 4-9**)**

For **Hesitation** in **Session 1**, a significant effect of quality of sleep (QoS) was observed in the **uncontrolled model** (B = 9.649, $p = 0.002$). This effect remained significant in the **half-controlled model** (B = 9.889, $p = 0.005$) and increased in the **fully controlled model** (B = 12.505, $p < 0.001$). This means a strong correlation that when hesitation increases, the quality of sleep decreases. Additionally, PSQI was negatively associated with hesitation in the fully controlled model (B = -0.110, $p = 0.001$).

In Session 2, the Time in Bed (TIB) derived from Actigraphy-2 analysis showed a significant negative association with hesitation across all models, which means short sleep is associated with increased hesitation (less recovery).

Smoothness (Table 4-9**)**

For **Smoothness** in **session 1**, quality of sleep exhibited a significant negative effect in the **uncontrolled model** (B = -0.132, p = 0.004), which remained significant in the **half-controlled model** (B = -0.118, p = 0.017) and the **fully controlled model** (B = -0.174, p < 0.001), which means better quality of sleep associated with increased Smoothness of movement. Additionally, Average sleep bouts were positively associated with Smoothness in the fully controlled model (B = 0.001, p = 0.024).

In **Session 2**, the variable time in bed (TIB) showed a positive effect on Smoothness in all models: **uncontrolled** (B = 0.003, p = 0.005), **half-controlled models** (B = 0.003, p = 0.003) and **fully controlled model** (B = 0.005, p < 0.001). However, the predictive value was low.

4.4 Discussion

In the third study, the relationship between sleep and motor function was examined in stroke participants. Sleep quality, duration, and continuity dimensions were selected, while sleep timing was excluded due to the extensive volume of variables already being examined. Both subjective and objective sleep assessment methods were applied to measure sleep.

There are varying perspectives on the reliability of sleep measurement methods. Actigraphy can misinterpret periods of inactivity as sleep (Laakso *et al.*, 2004; Fekedulegn *et al.*, 2020; Gottlieb *et al.*, 2021). Therefore, to enhance accuracy—particularly in cases involving low-functioning hemiparesis and fragmented sleep (Laakso *et al.*, 2004; Fekedulegn *et al.*, 2020; Gottlieb *et al.*, 2021) — two distinct analyses were conducted using actigraphy. In the first analysis, actigraphy data were analysed based on sleep and wake times derived from the sleep diary; in the second analysis, actigraphy data was analysed sorely by activity and light data. In addition to actigraphy, data from a 7-day sleep diary and the PSQI were also reported.

Subsequently, to investigate the relationship between sleep and motor function, a correlation analysis was conducted on sleep and motor function variables. This analysis reveals notable relationships between various sleep metrics and motor function outcomes in stroke participants. Specifically, compared with actigraphy data motor function, the coordination-2 variable was not significantly related to any actigraphy variables in both sessions. Smoothness was not associated with any actigraphy sessions in session 1, and in session 2, it has a moderate and significant relationship with TIB measured by actigraphy second analysis. The rest of the motor function variables were in a relationship between at least two sleep variables. Average sleep Bout is constantly related to motor function in every session and every actigraphy analysis type (ACT-1 and ACT-2). The Fugl-Meyer Assessment (FMA), a widely used tool for evaluating post-stroke motor function, was conducted to measure motor function along with biomechanical measurement. It was found that the FMA correlated with only one variable across the two sessions, highlighting the need for a more comprehensive assessment of recovery.

The final assessment involved regression analyses to identify the sleep variables most significantly associated with recovery outcomes. Sleep variables that showed correlations with motor function on three or more occasions were included in this analysis alongside all biomechanical variables. The regression analyses were conducted using three models: an uncontrolled model, a partially controlled model (adjusting for age and gender), and a fully controlled model (adjusting for age, gender, and mental health).

In the fully controlled model, **average sleep bouts** measured by actigraphy emerged as the most strongly correlated variable, significantly linked to five motor function variables across the two sessions. This variable was followed by **time in bed** (measured by actigraphy), **self-reported sleep quality**, and **sleep efficiency from the sleep diary**, each correlated with three motor function variables. Notably, the simple question, "How was your sleep quality?" was highly informative; better sleep quality correlated significantly with motor function outcomes.

Moreover, the average duration of sleep bouts emerged as the variable most strongly associated with motor function, while total time in bed, sleep efficiency, and the PSQI global score were also related but with fewer associations than the average sleep bouts.

This suggests that consolidated sleep episodes may have a stronger relationship with motor function than overall sleep duration or perceived sleep quality.

The subjective sleep diary data, collected over one week, suggest that the sample exhibits only mild levels of poor sleep. However, when considering the qualitative data from the PSQI, which requires participants to reflect on their sleep over the past month, a more diverse range of sleep patterns becomes apparent. Specifically, 35 out of 44 participants reported experiencing difficulties in maintaining sleep during at least one of the two assessment sessions. A summary of these qualitative responses is provided in Appendix 19.

Another point of consideration relates to the Participant Information Sheet, which stated that the study aimed to investigate the effect of sleep on motor function. This wording may have influenced some individuals' decisions to participate. However, it is unclear whether this had a meaningful impact on the characteristics of the sample, as participants were not explicitly asked about their reasons for enrolling.

4.4.1 Discussion of Findings in Context of Previous Research

Most studies investigating the relationship between sleep and motor function focus on the acute and subacute phases (Aaronson *et al.*, 2015; Yeh *et al.*, 2017; Ye *et al.*, 2018). In contrast, this study primarily involves a predominantly chronic stroke cohort, with only 5 out of 44 participants being within six months post-stroke. Additionally, this study predominantly includes patients with mild stroke severity. The unique feature of this study is that biomechanical assessment were utilised, which is recommended to assess motor function (Kwakkel *et al.*, 2017) Despite participants in this study being largely in the chronic phase, multiple associations between sleep and motor function were identified.

Davis *et al.* (2019) and Silva *et al. (*2021) also included chronic stroke patients, while Sonmez and Karasel (2019) involved a mixed-phase stroke cohort, assumed to be predominantly chronic based on mean values of time after stroke. In these studies, a relationship was found between sleep and motor function. Sleep quality was measured using the PSQI in both Silva *et al. (*2021) and Sonmez and Karasel (2019). Davis *et al.* (2019) found that only the daytime dysfunction and habitual sleep efficiency subcomponents of

the PSQI were correlated with motor function. The daytime function is negatively associated with 6MWT (6-minute walking test) after accounting for age, sex, functional capacity, and cognitive function. Habitual sleep efficiency was significantly and positively associated with 6MWT.

In contrast, Fleming *et al. (*2021) study, which focused on chronic stroke patients, found no connection between motor impairment and any sleep measures (both subjective and objective). The Fugl-Meyer Assessment (FMA) was also used in this study to assess motor function. However, while Fleming et al. (2021) used the upper-limb FMA, the current study focused on the lower-extremity version of the FMA. The current study found a significant association between motor function and one specific sleep variable—the time in bed (TIB) derived from the sleep diary—but only in Session 1. The limited association found with the FMA in this study may be due to a ceiling effect of the FMA, with many participants reaching the maximum score on the FMA (24 out of 44 participants). This ceiling effect likely reduced the ability to detect a broader range of motor impairments and their relationship with sleep.

Research on acute and subacute stroke groups has generally found stronger associations between sleep quality and motor function. For example, Fleming, Smejka and Slater (2020) included acute stroke patients as well as individuals with traumatic brain injuries. They measured motor function using the Sleep Fragmentation Index, calculated from wake after sleep onset (WASO) and frequency of awakenings. They found that the Sleep Fragmentation Index was significantly correlated with the Action Research Arm Test (ARAT) and the Fugl-Meyer Assessment (FMA), which indicates poorer motor function associated with more fragmented sleep.

Another study by Joa *et al.* (2017) examined mild and moderate stroke patients in an acute hospital setting and found that sleep disturbances were associated with reduced motor function measured by the Korean Berg Balance Scale (K-BBS). For patients with moderate stroke severity, balance improvements were significantly lower in the presence of sleep disturbance. However, balance improvements in the mild stroke group were not significantly associated with sleep quality.

Moon *et al.* (2018) conducted a retrospective study where sleep disturbance was identified by reviewing medical records. The study found that patients with sleep disturbances were

generally older and had poorer balance and gait function. Balance and gait function, as measured by the Berg Balance Scale (BBS) and Functional Ambulation Category (FAC), were also predicted by initial BBS scores and the presence of sleep disturbances. Additionally, the 10-metre walking velocity was significantly associated with initial BBS, time since stroke onset, and sleep disturbance. This study highlighted that sleep disturbances had a negative impact on functional outcomes, particularly in balance and gait; however, the confounding effect of age was not controlled for.

The evidence suggests a complex relationship between sleep and stroke recovery. Variability in findings may stem from differences in study populations and the specific aspects of motor function assessed. While sleep disturbances in acute and subacute phases have been linked to poorer recovery outcomes, results in chronic cohorts remain less clear.

4.4.2 Strengths and Limitations

This study possesses several strengths. First, mental health assessments were incorporated, as mental health problems, such as depression and anxiety, can significantly influence sleep quality (Nutt, Wilson and Paterson, 2008; Oh *et al.*, 2019). Mental health issues were examined as a confounding factor to clarify the relationship between motor function and sleep.

Secondly, biomechanical assessments were employed to evaluate participants' motor function for a more nuanced analysis. Furthermore, sleep dimensions -sleep continuity, duration, and quality- were measured using both objective and subjective methods. The specificity of these measures facilitated an in-depth examination of the interplay between sleep and motor function. As a result, significant correlations were identified between sleep and stroke recovery, even within a sample predominantly composed of chronic stroke patients with mild impairments.

However, one limitation of this study is the final sample size. While the initial power calculation indicated that 54 participants were needed to estimate the intra-class correlation coefficient (ICC) with a 95% confidence interval width of no more than 0.15, only 44 stroke patients were ultimately recruited. This smaller sample size may have affected

the precision of the ICC estimates. It may also have reduced the statistical power to detect certain levels of agreement. Furthermore, the reduced sample size may limit the generalisability of the findings to a broader stroke population. Although the same sample was used to explore associations between sleep and motor function, no separate power calculation was conducted for this analysis. Nonetheless, the findings provide exploratory insights that are relevant within the context of previous research in similar populations.

A methodological challenge also arose from the biomechanical assessment of the STW movement, which was found to have low test-retest reliability in the reliability study. This study was conducted simultaneously with the stroke study due to COVID-related restrictions, which limited access to the lab and required data collection within a restricted timeframe. At that stage, the test-retest results were not yet available, so it was not known that the STW test might lack clinical justification.

STW is a multiphase movement, making it inherently more complex. A simpler functional movement, such as the sit-to-stand (STS) test with a more standardised starting position, could have been considered as an alternative to STW. However, STS would not have allowed for the measurement of key aspects assessed in this study, such as hesitation or coordination (involving overlapping opposite movements). Instead, as an additional measure, it could have provided insight into symmetry by assessing load distribution between the legs. Another important consideration is that STS is not as functionally relevant to daily life as STW, since, in most everyday scenarios, the transition from a sitting position is followed by walking. Furthermore, movements restricted to a single axis or involving only one or two joints may yield more reliable measurements (e.g., maximal flexion angles), but their relevance to daily functional activities is limited (Engdahl and Gates, 2019; Deane *et al.*, 2020). Therefore, while alternative tests might offer improved reliability, they may not adequately capture the dynamic nature of lower extremity function in real-world contexts (Deane *et al.*, 2020).

One of the limitations is that extreme discrepancies were observed between actigraphy and subjective measurements in the TST (Total Sleep Time), SE (Sleep Efficiency), and WASO (Wake After Sleep Onset) variables. Specifically, actigraphy measurements for these variables were significantly lower than those reported in the literature, likely due to oversensitivity in the actigraphy analysis.

Upon closer inspection of actigraphy data for each participant, it became evident that many participants exhibited low, constant activity levels post-sleep, which the algorithm interpreted as wakefulness. This interpretation led to inflated WASO values in the actigraphy data, contrasting sharply with the much shorter WASO times reported in participants' sleep diaries. One possible explanation is that, while GENEactiv watches were used, the data were analysed using Philips Actiware software, as recommended by the GENEactiv company. However, the algorithm in Philips Actiware may be optimised for data from Philips Actiwatches, making it oversensitive to data collected by GENEactiv devices. For sample actigraphs from participants, please refer to Appendix 18.

Despite this, the reliability of analysing relationships between sleep and motor function is unaffected, as the same algorithm was consistently applied to all participants. However, direct comparisons between objective (actigraphy) and subjective (sleep diary, PSQI) sleep variables could introduce bias, so these variables were not compared directly. Although prior studies (e.g., Tomita et al. (2013)) report some disagreement between objective and subjective sleep measures, the discrepancy in our study was considerably more extensive due to possible algorithm oversensitivity. This situation was impacting on TST, SE, and WASO. Since TST represents total sleep time with midnight awakenings removed, SE, calculated as TST divided by TIB (time in bed), was also affected. WASO, which reflects wake time after sleep onset, was the most impacted by the algorithm's sensitivity, with actigraphy values exceeding sleep diary reports by four times.

Another limitation relates to the use of actigraphy watches in stroke patients, particularly when worn on the affected hand. This may affect data reliability. Three participants had to wear actigraphy watches on only one wrist due to the need to safely remove the device. Since stroke can significantly impact voluntary movement, this may influence the accuracy of movement-based sleep assessments. This presents a challenge when interpreting actigraphy data, as the sensor may not distinguish between true sleep-related immobility and reduced voluntary movement due to stroke-related deficits. However, this issue affected only three participants, and for the others, more reliable data from both wrists were able to be analysed.

Access to clinical information and participant characteristics posed further limitations. Restricted access to medical records, including brain imaging and detailed reports. Thus,

reliance on participants' self-reported stroke diagnoses and the timing of sleep events was necessary. This approach may have introduced inaccuracies. Additionally, the sample comprised solely community-dwelling stroke survivors, which restricts the generalisability of the findings to the early stages of post-stroke recovery, during which sleep patterns may differ. Consequently, the results may not be applicable to the acute stroke population. The study by Fleming *et al*. (2024) encountered similar limitations. Furthermore, although biomechanical measurements were available for the non-stroke participants, the absence of sleep data from this group limited the ability to directly compare sleep patterns between stroke survivors and participants without stroke. Lastly, the lack of polysomnography (PSG) which is considered the gold standard for sleep measurement, may have limited the accuracy of the sleep metrics.

Although participants were recruited from all phases of stroke recovery, most were in the chronic stage, with a mean time since stroke of six years. Given this chronicity, a two- to three-month period was insufficient to capture meaningful changes in stroke recovery. Therefore, the term 'motor function' was used instead of 'motor recovery' to more accurately reflect the scope of the study.

An important factor not explicitly addressed in the experimental design was post-stroke fatigue (PSF). Fatigue is a frequent and debilitating consequence of stroke, affecting up to half of survivors in the chronic phase (Winward et al., 2009; Rahamatali et al., 2021). Moreover, fatigue has been shown to hinder motor (Choi-Kwon et al., 2005; Naess et al., 2005) and cognitive function (Maaijwee et al., 2015). Fatigue is closely associated with subjective sleep metrics, including sleep quality (Lerdal et al., 2011; Suh, Choi-Kwon and Kim, 2014), daytime sleepiness (Suh, Choi-Kwon and Kim, 2014; Duncan et al., 2015), and sleep disturbance (Naess et al., 2012; Wang et al., 2014; Galligan et al., 2016). The omission of PSF in the experimental framework may have influenced the findings, as participants experiencing fatigue could have exhibited altered performance levels, potentially confounding the interpretation of stroke-related work capacity and recovery patterns.

Another relevant omission in the study design was the lack of measurement of daytime sleep or naps. Daytime napping and sleepiness provide valuable insights into overall sleep behaviour and its impact on cognitive and physiological functions. Recent research has highlighted the complex relationship between daytime napping and health outcomes. For

instance, a 2024 meta-analysis (Yang et al., 2024) indicates that habitual naps exceeding 30 minutes are associated with increased risks of all-cause mortality, cardiovascular disease, and metabolic disorders. In contrast, shorter naps of less than 30 minutes did not show significant adverse effects, suggesting that nap duration plays a critical role in health outcomes.

This study specifically focused on nocturnal sleep to maintain consistency in data collection and analysis. The decision to exclude nap data was based on methodological and practical considerations. Nighttime sleep patterns tend to be more consistently structured and can be assessed more reliably using standard tools such as actigraphy or polysomnography. In contrast, daytime naps vary significantly in timing, duration, and frequency, making them more difficult to measure accurately, particularly in home-based settings.

Supporting this, a recent systematic review (Li et al., 2023) highlighted the absence of a standardised approach for assessing daytime napping. It noted that self-reported nap data could be affected by recall bias, particularly in older adults with cognitive impairment, while objective methods like actigraphy may overestimate nap duration by misclassifying periods of inactivity as sleep.

By concentrating exclusively on nocturnal sleep, this study aimed to minimise confounding from nap-related variability and measurement challenges. However, the omission of nap data may limit the ability to capture total 24-hour sleep behaviour, especially in individuals who compensate for poor night-time sleep with daytime rest. Notably, the Karolinska Sleep Diary (KSD) used in this study does not include items on daytime napping, unlike the Consensus Sleep Diary (CSD), which provides a more comprehensive view of sleep-wake patterns. This methodological choice may have constrained the interpretation of total sleep quantity and continuity across the diurnal cycle. Future research should consider incorporating tools such as the CSD or advanced passive monitoring technologies to better capture both nocturnal and daytime sleep in post-stroke populations (Ravindran et al., 2023).

Another limitation is the length of the testing sessions: On average, the sessions lasted around two hours. This duration included the sit-to-walk tests, the Fugl-Meyer Assessment,

instructions for completing the sleep diary and other questionnaires. While every effort was made to minimise participant fatigue, the extended duration may still have affected performance and engagement. Rest breaks were allowed as needed, and participants were explicitly asked if they wished to pause at any point.

To further reduce testing time and minimise fatigue caused by frequent position changes, assessments conducted in the supine and sitting positions were carried out together whenever possible. This adjustment helped streamline the protocol and maintain participant comfort throughout the session. However, momentary fatigue during the session was not formally measured. Its omission represents an additional limitation of the study.

A final limitation of this study is the lack of systematic control for medications or stroke-related complications that may have influenced sleep patterns. Common post-stroke issues such as nocturia, bladder dysfunction, or the use of sedatives, antidepressants, and antihypertensives are known to affect sleep architecture and quality (Cai, Wang & Yang, 2021; Agapiou et al., 2024). However, this study was deliberately designed as a pragmatic investigation, aiming to capture real-world associations between night-time sleep and motor function rather than isolate all potential confounders. While these influences were not formally analysed, they were reported through open-ended responses in the PSQI and are summarised in Appendix 19 to provide additional context regarding participants' sleep-related experiences.

4.4.3 Implications for Future Studies

In this study, a distinction was made between total time in bed (TIB) and time in bed for sleep (TIB for sleep). According to the data from the sleep diary, the TIB variable refers to the overall time participants spend in bed. Meanwhile, TIB for sleep starts when they attempt to fall asleep and ends with wake-up time. The difference between the means of these two variables was about 100 minutes. This distinction reveals that participants often engaged in pre-sleep activities, such as reading, watching television, or using digital devices, and post-sleep behaviours like lying awake or mentally preparing for the day (Nixon *et al.*, 2009; Exelmans and Van Den Bulck, 2016). While these activities extend the time spent in bed, they do not contribute to actual sleep duration.

Additionally, in clinical or supported settings, the presence of caregivers may also affect this gap. Caregivers may assist participants into bed earlier than their natural sleep onset time, as part of standard care routines or due to practical constraints. This support can cause the actigraphy to register an earlier TIB than the physiological attempt to sleep, further increasing the discrepancy (Byun *et al.*, 2020).

This routine underscores the importance of considering lifestyle and bedtime habits when measuring sleep metrics. However, as indicated by a recent literature review, only 16 out of 40 questionnaires asked about the first attempt to sleep that distinguishes time in bed from time in bed for sleep (Robbins *et al.*, 2021). This inconsistency also appears in other survey questions measuring sleep-related metrics: Variability exists in questions about sleep duration, bedtime, and wake-up time, with distinctions in the context, timeframe, and event definitions used. Such differences hinder comparability and data harmonisation across studies (Robbins *et al.*, 2021). Therefore, in line with Robbins *et al*. (2021) developing a standardised set of optimally worded questions to assess sleep metrics in epidemiological studies could improve data consistency for future research.

This study incorporated mental health assessments following a stroke but did not include evaluations of physical activity. Since mental health, activity levels, sleep, and motor function are interconnected (Sandberg *et al.*, 2001; Shepherd *et al.*, 2018; Park, 2019; Scott *et al.*, 2021), incorporating mental health and activity measures in future research would provide a more comprehensive understanding of their relationship. In detail, stroke often leads to significant physical impairment, which can reduce physical activity levels (Ezeugwu and Manns, 2017). This decreased activity, in turn, may contribute to poorer sleep quality, creating a loop where physical impairment exacerbates inactivity, impacting sleep (Smith *et al.*, 2024). Rand *et al.* (2009) support this by demonstrating that individuals with stroke generally exhibit low activity levels, which may be partly due to the physical limitations imposed by the stroke itself. Studies indicate that post-stroke individuals spend approximately 75% of their waking hours in sedentary behaviours, with minimal physical activity such as walking (Ezeugwu and Manns, 2017). Such sedentary lifestyles are further associated with adverse health consequences, including poorer sleep hygiene, increased depressive symptoms, and more frequent sleep disturbances (Davis *et al.*, 2019). This evidence points to the importance of sleep and physical activity as potential intervention targets to improve recovery outcomes. (Smith *et al.*, 2024). Therefore**,** future studies should

explore the intricate relationships between sleep, activity, mental health and motor function.

This study employed an observational design with broad inclusion criteria to explore the overview of the relationship between sleep and motor function in stroke survivors. However, more controlled studies are needed to enhance our findings' robustness. Future research should focus on carefully selected participant groups that consider stroke severity, chronicity, the presence of sleep disorders, and the use of sleep medicine.

Additionally, more long-term studies are necessary to elucidate the complex interplay between sleep and stroke recovery over time. In line with the study by Frange, Murray and Coelho (2023), longitudinal studies with multiple measurement points are needed to clarify how sleep influences post-stroke recovery trajectories. Addressing these gaps could enable future studies to provide invaluable insights for clinical practices, ultimately improving the recovery process for stroke survivors.

5 Chapter 5: Discussion

5.1 Key Findings and Implications

Sleep facilitates the consolidation of motor skills, enhancing stroke recovery outcomes (Kaneko *et al.*, 2003; Fulk, Duncan and Klingman, 2020). Moreover, sleep problems exacerbate cognitive and emotional challenges, such as reduced attention, anxiety, and depression, which hinder engagement in rehabilitation and further worsen outcomes (Pearce *et al.*, 2016; Glozier *et al.*, 2017; Li *et al.*, 2019). Recognising the significant impact of sleep on stroke recovery, the aim of this thesis was to explore the relationship between sleep and motor function following stroke.

Three studies were conducted to address this aim. The first was a systematic literature review examining existing research on the connection between sleep duration and quality and motor function and examining research gaps. The second study investigated the test-retest reliability of biomechanical measures of movement fluency (hesitation, coordination, and smoothness) in the non-stroke group. This study laid the foundation for the robust use of biomechanical measures in subsequent analyses. The third study aimed to determine how sleep dimensions, measured by objective and subjective tools, are associated with motor function with adjustments for demographic and mental health.

The results from the first study indicated a general association between sleep and stroke recovery, although the strength of this relationship varied across studies. The diversity of measurement tools and stroke populations in these studies further complicates drawing clear conclusions. Notably, none of the reviewed studies used biomechanical assessment methods, which were recommended in a recent roundtable (Van Criekinge et al., 2024) to improve accuracy by detecting subtle changes in recovery and reducing compensatory movements. Therefore, biomechanical assessment methods are used in this project to investigate the relationship between sleep and motor function.

The second study focused on the test-retest reliability of fluency metrics in the sit-to-walk task, given its frequency in daily life but relative scarcity in research. Results from this study indicated that none of the fluency metrics achieved clinically acceptable test-retest reliability (≥0.75) (Portney and Watkins, 2009).

The third study examined the relationship between sleep and motor function in stroke participants. Both subjective and objective sleep measures were used, including actigraphy, sleep diaries, and the Pittsburgh Sleep Quality Index (PSQI). Although the study population primarily comprised chronic stroke patients with mild impairments, a meaningful association between sleep and motor function, measured by fluency metrics of STW, was observed. The Fugl-Meyer Assessment (FMA), a commonly used tool for evaluating post-stroke motor function, only correlated with one variable across two sessions.

Considering the three studies together, the research partially achieved its overall aim of exploring the relationship between sleep and motor function following stroke. The systematic review provided a broad synthesis of existing evidence, identifying a general association between sleep and stroke recovery but it highlights significant variability in findings due to methodological differences and diverse populations. These limitations prevented the derivation of definitive conclusions. The second study explored the reliability of biomechanical measures of STW, finding that these measures did not achieve clinically acceptable reliability. The third study demonstrated associations between sleep variables and motor function. However, the less reliable nature of the biomechanical measures identified in the second study tempers the strength of these findings.

The findings from this study revealed that average sleep bouts measured via actigraphy had the strongest correlations with five motor function variables across two sessions, followed by time in bed, sleep diary-based sleep quality, and sleep efficiency, each correlating with three motor function variables. Interestingly, a single question regarding perceived sleep quality was also significantly linked to motor function. Overall, average sleep bouts—reflecting the duration of continuous sleep segments—appeared to be more indicative of recovery outcomes than traditional measures like total time in bed or the PSQI global score.

These results align with previous literature that identified average sleep bouts and the frequency of awakenings after sleep onset as indicators of sleep disturbances, often assessed within the context of insomnia (American PsychiatricAssociation, 2000; Joa *et al.*, 2017; Fleming *et al.*, 2021). Moreover, insomnia was not only linked with poor motor function (Matas, Amaral and Patto, 2022); it was also linked with an increased risk of suicide in stroke patients (Tang *et al.*, 2011).

The importance of measuring sleep quality is evident, given its significant role in health and recovery (Duss *et al.*, 2017). However, there is no universally accepted definition of sleep quality (Krystal and Edinger, 2008). Key components often include sleep duration, periods of wakefulness before and after sleep onset, and feelings of refreshment upon waking (Harvey *et al.*, 2008). While self-reported sleep quality correlated with some objective assessments, it did not completely align with objective measures (Kline, 2013b). This suggests that sleep quality should continue to be addressed as a separate, subjective metric, as it may signal underlying severe issues and warrant further investigation into sleep problems in stroke patients. In alignment with this perspective, this study examined sleep quality as a distinct and subjective factor, and it revealed it to be one of the variables most strongly associated with motor function.

Future research can expand on these findings by incorporating biomechanical assessments to further explore the relationship between sleep and motor function. These measurements are particularly recommended for evaluating motor function (Kwakkel *et al.*, 2017). However, findings from the second study emphasise the need to refine these measures to enhance their robustness and clinical applicability before broader implementation.

This study focused on assessing sleep quality, duration, and continuity, specifically during night sleep. Sleep timing variables, such as circadian rhythm and sleep midpoint assessments, were excluded. including these assessments, which may further illuminate how this dimension of sleep is elated with motor function, were not investigated in this study.

Additionally, this study adopts a comprehensive approach by examining the relationship between sleep and motor function in stroke patients. However, it does not exclude, or subgroup participants based on factors such as the use of sleep medications, the presence of sleep disorders, the phase of stroke recovery, stroke severity, or the location of the brain injury. These are known to influence both sleep patterns and recovery outcomes, yet their effects were not specifically accounted for in this study. By not isolating these variables, this research provides a more general overview of the relationship between sleep and motor function. However, future research may benefit from addressing these factors to more precisely understand sleep's role in post-stroke recovery.

Another important limitation is the absence of analysis on the combined effects of post-stroke fatigue, sleep, and recovery. Post-stroke fatigue is a common and often disabling condition, with reported prevalence ranging from 23 to 75 percent depending on definitions and patient characteristics (Choi-Kwon and Kim, 2011). Research indicates that post-stroke fatigue can significantly impair mobility, hinder functional recovery, and limit community participation in stroke survivors (Usman, Wong and Ng, 2024). These findings highlight the importance of addressing both fatigue and sleep disturbances in post-stroke rehabilitation to enhance recovery and improve quality of life. However, the present study did not explicitly examine the interaction between fatigue, sleep, and recovery. Fatigue may have influenced participants' engagement in rehabilitation tasks, which could affect the interpretation of motor and cognitive recovery outcomes. Future research should incorporate assessments of both sleep and fatigue to provide a more comprehensive understanding of their combined influence on stroke recovery and rehabilitation progress.

5.2 Bridging the Gap Between Laboratory and Real-World Movement Assessments

The use of neuromechanical measures to examine the relationship between sleep and stroke recovery presents a novel approach. Laboratory studies of human movement, includes assessments of flexion-momentum and postural stability, require specialised equipment, such as force plates and motion-capture systems, to ensure objective measurement. However, this environment can influence the behaviour it seeks to measure, thus limiting generalisability to real-world scenarios.

Human movement is sensitive to numerous factors that vary in daily life—reaction time, balance, strength, and emotional state, among others (Tiedemann, Sherrington and Lord, 2005; Takayanagi *et al.*, 2019). Research shows that certain aspects of movement, such as average gait speed, are slower in real-world environments compared to the lab. It emphasises that lab findings might not fully capture real-world movement patterns (Takayanagi *et al.*, 2019). Furthermore, lab settings often lack the authentic environmental cues and real-world contexts that can influence participants' behaviour. Moreover, participants may alter their behaviour due to the awareness of being observed (Levitt and List, 2007).

This thesis aimed to address these limitations by integrating real-world tasks to introduce purposeful actions into the experimental setup; for the sit-to-walk movement, participants were asked to answer a phone placed 3 meters away. Nevertheless, the lab's highly controlled nature could reduce naturalistic behavioural responses, affecting the external validity of the data (Levitt and List, 2007). Despite these limitations, laboratory-based research remains essential for generating controlled, valid data on human movement. Translating these findings to clinical practice requires further innovation to bridge the gap between laboratory and real-world conditions. For example, Granat, (2012) suggests integrating events, such as sitting and standing, into activity counts to analyse the activity data in more detail, like in a lab environment. Emerging tools like wearable technology (Iosa *et al.*, 2016) and markerless motion-capture systems also offer promising solutions to minimise real life and lab differences and enables more practical assessments not only in clinical settings but also in daily life measurements.

A scoping review from Benson *et al.* (2022) explored the use of wearable technology in running, particularly inertial measurement units (IMUs), to bridge the gap between laboratory and real-world conditions in running biomechanics research. Laboratory studies are essential for generating controlled, valid data, yet they often do not accurately mirror real-world scenarios. Real-life environments introduce complex factors—such as uneven surfaces, variable weather, and changing movement speeds—that significantly influence biomechanical patterns. Further supporting this, Tamburini *et al.*, (2018) found that gait variability indexes were influenced by both the environment and type of walking, while stability indexes such as harmonic ratio remained unaffected. These findings highlight how real-world variability impacts assessments and demonstrate the potential of wearable sensors to capture the natural adaptability of movement, which traditional laboratory setups cannot. Therefore, incorporating wearable technology allows for the monitoring of naturalistic movement, helping to overcome the limitations posed by laboratory-based studies and it ensures that the data collected is more reflective of actual participant behaviour in their daily lives.

5.2.1 Motor Function Assessment: Limitations and Recommendations

Although the Sit-to-Walk (STW) task, combined with Vicon motion analysis, provides detailed kinematic insights, its usefulness in clinical stroke populations is limited. The STW

movement is inherently complex. It involves multiple sequential phases, including sit-to-stand, balance control, and gait initiation. These phases require significant standardisation to produce reliable and interpretable data. However, achieving this level of standardisation is difficult in clinical settings, especially among patients with cognitive, balance, or mobility impairments.

In addition, the Vicon system, while highly accurate, depends on specialist equipment, trained personnel, and controlled laboratory conditions. This makes it largely impractical for routine clinical use. Another limitation is that some participants may be unable to complete the full STW task due to motor impairments or fatigue. In such cases, surface electromyography (EMG) can still provide valuable insights. Even without full task execution, EMG allows for the assessment of muscle activation patterns, compensatory strategies, and movement intention. These aspects are clinically meaningful when evaluating motor function.

Given these challenges, alternative tasks such as Sit-to-Stand (STS) may offer a more practical option for assessing motor ability. STS is less complex, easier to standardise, and more tolerable for stroke survivors with varying levels of function. However, simplifying the task comes with a trade-off. Specifically, it omits important balance and gait transition data that are uniquely provided by the STW sequence.

To bridge the gap between laboratory precision and clinical feasibility, future research could explore the use of wearable inertial measurement units (IMUs) with simpler functional tasks. These devices can be combined with EMG sensors when feasible, providing additional insight into muscle activation patterns. This hybrid approach would allow for scalable, real-world assessments while still capturing key motor and neuromuscular parameters relevant to stroke recovery. IMUs have demonstrated reliable performance in measuring balance in stroke survivors. They are also sensitive to subtle changes across a wide range of functional abilities (Felius *et al.*, 2022). This makes them a promising tool for both clinical evaluation and long-term monitoring of recovery progress.

5.3 Future Directions and Suggestions for Clinical Practices to Address Sleep Problems in Stroke Recovery

5.3.1 Undetected Sleep Disorders: A Hidden Challenge in Stroke Recovery

This study demonstrated a significant relationship between subjective sleep quality and motor function, which implies the need to identify and address sleep problems to promote motor function. This aligns with the growing recognition that undetected sleep disorders, such as obstructive sleep apnoea (OSA), insomnia, and other sleep-breathing disorders, are not only common but also prognostically significant in stroke populations (Pajediene *et al.*, 2020). In detail, more than half of stroke patients experienced new or exacerbated sleep issues, with sleep-breathing disorders and insomnia identified as significant prognostic factors for recovery (Pajediene *et al.*, 2020). Common issues included insomnia (89.4%), sleep apnoea (95.5%), periodic limb movement disorder (66.7%), and parasomnias (63.6%), with many cases previously undiagnosed. Polysomnography (PSG) revealed reduced sleep efficiency, prolonged onset, fragmented sleep, and an increase in lighter sleep stages—findings consistent with prior research (Baglioni *et al.*, 2016). While sleep-breathing disorders were most common, other conditions like REM sleep behaviour disorder also presented, underscoring the need for a thorough diagnosis (Pajediene *et al.*, 2020).

Apart from sleep's effect on motor function, undetected sleep problems can pose life-threatening risks: Tang *et al.*, (2011) highlight the mental health risks associated with sleep disturbances, demonstrating that frequent awakenings—a hallmark of 'middle insomnia'—significantly increase the risk of suicidal ideation (SI) in stroke patients, independent of depression and fatigue.

These results suggest that addressing sleep problems can improve motor function and reduce the risk of suicidal ideation (SI) in stroke survivors. Therefore, integrating sleep assessments into routine stroke evaluations is essential.

5.3.2 Integrating Sleep Assessment into Routine Clinical Practice

Sleep disturbance is often under-recognised during routine healthcare encounters, despite its significant impact on health and recovery outcomes. This is especially important in populations with increased vulnerability, such as post-stroke patients (Hanson and Huecker, 2025). There is a pressing need for greater awareness and structured approaches to assess and manage sleep-related issues in such settings.

Sleep assessment is feasible within routine clinical practice and can be administered by allied health professionals. This makes it particularly suitable for under-resourced services (Hulst et al., 2020; Basheti et al., 2023). In stroke care specifically, where sleep influences fatigue, cognitive performance, and rehabilitation outcomes, integrating sleep assessment may offer a cost-effective strategy to enhance recovery.

Our study used a single-item self-report question: "How would you rate your sleep quality?" on a scale from 1 to 9. This practical and low-burden tool provided meaningful insights. It aligns with implementation research that supports brief and scalable assessments in everyday care. For instance, Chaput and Shiau (2019) recommend a concise six-question screening set. It is adapted from validated instruments such as the National Sleep Foundation's Sleep Health Index. These questions assess sleep duration, sleep quality, consistency of sleep timing, daytime alertness, symptoms of insomnia, and signs of sleep apnoea such as loud snoring. These tools require less than two minutes to administer. They provide an efficient way to evaluate sleep health in busy clinical environments.

When poor sleep is reported, more comprehensive, validated instruments can be used to stratify risk. These include the Insomnia Severity Index (ISI) (Bastien, 2001), the Pittsburgh Sleep Quality Index (PSQI) (Buysse et al., 1989), and the Sleep Condition Indicator (SCI) (Espie et al., 2014). For individuals with persistent or clinically significant sleep problems, further investigation may be warranted. This may involve objective measures such as actigraphy or referral to a specialist. A tiered approach supports efficient resource use and enables timely intervention.

System-level innovations within the NHS demonstrate how sleep health can be addressed effectively and at scale. For example, NHS England has implemented "straight to test" and

“direct to treatment” pathways. These allow patients to be referred directly for diagnostic tests such as respiratory polygraphy. This can happen without a prior consultant review. When obstructive sleep apnoea (OSA) is diagnosed and there are no complications, patients can begin CPAP therapy before seeing a consultant. This model has improved efficiency, reduced waiting times, and prioritised complex cases for specialist input (NHS England, 2024).

These pathways are supported by structured referral frameworks. They require essential clinical details such as occupation (for example, HGV drivers), Epworth sleepiness scores, driving status, pregnancy, and comorbidities such as cardiovascular disease or hypercapnoea. High-priority groups, including patients with stroke or heart failure, are fast-tracked. This helps to minimise delays in treatment initiation (NHS England, 2024).

Another example is the Liverpool Sleep Service. It has implemented a digital triage system using a computer-guided consultation (CGC). Paramedical staff, supported by clinical decision tools, assessed over 1,000 patients with suspected OSA. Only 14 percent of these cases required consultant input. This resulted in a weekly reduction of approximately 12 hours of consultant clinic time (NHS England Transformation Directorate, 2022).

These examples show that sleep can be effectively assessed and managed during routine healthcare. This can be achieved using brief tools, multidisciplinary teams, and innovative service models. Recognising sleep as a vital clinical parameter may contribute to better outcomes in stroke rehabilitation and improve overall healthcare delivery.

A study evaluating the implementation of routine sleep screening in clinical settings could adopt a hybrid type II implementation-effectiveness design (Curran *et al.*, 2012). For example, this could involve embedding a single-item sleep quality question, such as “How would you rate your sleep quality?” rated on a 1 to 9 scale, into electronic health records across selected services.

This design allows for the simultaneous assessment of both clinical outcomes and the implementation process (Curran et al., 2012). The implementation strategy could include staff training, workflow integration, and the use of automated prompts to encourage consistent screening.

The study would measure both effectiveness and implementation outcomes. Effectiveness outcomes could include improvements in the identification of clinically significant sleep disturbances, enhanced access to interventions, and patient-reported improvements in fatigue, mood, or quality of life. Implementation outcomes would be assessed as proposed by Proctor *et al.* (2011). These could include acceptability, which refers to staff and patient perceptions of the screening's suitability, assessed through structured feedback or interviews. Fidelity would measure the degree to which clinicians follow the screening and follow-up protocol, including consistent use of validated tools such as the PSQI or ISI. Implementation cost would cover resources required for training, system integration, and staff time. Appropriateness would assess the perceived relevance of routine sleep screening within stroke care pathways and broader clinical settings. Adoption would measure the uptake of the screening tool by clinicians and services. Reach would evaluate the proportion of eligible patients screened and referred. Feasibility would consider the practicality of delivering sleep screening within existing clinical workflows and resource constraints.

To understand why implementation succeeds or fails, the study would apply the Consolidated Framework for Implementation Research (CFIR) (Damschroder et al., 2009), a widely used framework in health services research. CFIR provides a structured approach to understanding how various factors—such as the characteristics of the intervention, the organisational context, staff readiness, and the implementation process—affect the integration of innovations into routine care (Damschroder *et al.*, 2009). It supports systematic identification of barriers and facilitators, which can inform adaptations to improve scalability and sustainability.

5.3.3 Exploring Interventions for Post-Stroke Sleep Disorders: A Path to Improved Motor Function

Self-reported sleep quality often correlates closely with underlying sleep disorders, which affect approximately half of the stroke population (Johnson and Johnson, 2010; Baylan *et al.*, 2020; Hasan *et al.*, 2021). Given the prevalence of sleep disorders and their impact on motor function, further exploration of individual sleep challenges and underlying causes could provide actionable insights to solve sleep problems and improve post-stroke motor

function. For this aim, qualitative studies are also needed to obtain a comprehensive analysis of sleep problems.

Addressing the reason for sleep problems is the first step only. Studies are also needed to focus on strategies for improving sleep quality and examining the direct effects of such improvements on motor function outcomes. Recent research is exploring which interventions can most effectively improve sleep recovery in stroke patients. A systematic review by Lowe, Neligan and Greenwood (2020) suggests clinically viable interventions, such as cognitive behavioural therapy for insomnia (CBTi) and melatonin supplementation, as potential options for mitigating sleep disorders in stroke patients. However, studies on the effects of these interventions on motor function remain limited, with much of the research conducted either in animal models or at the molecular level in human studies.

Animal studies have shown promising results. For instance, (Hao *et al.*, 2021) demonstrated that melatonin administration in rats positively influenced motor function post-stroke, supporting melatonin's potential as a therapeutic option. Broader reviews of melatonin's effects on stroke population indicates that melatonin-based therapies may offer neuroprotective effects by reducing neuroinflammation and accelerating brain tissue recovery in ischemic stroke (Sadanandan *et al.*, 2020; Tozihi *et al.*, 2023). Likewise, Zhong *et al.* (2024) studied the effect of zolpidem, a sleep medication, in a rat model and found that it improved both sleep quality and motor function. The findings from these studies provide a foundation for future research to explore whether treating sleep problems with similar interventions can improve motor function in stroke patients.

Future clinical studies could directly assess whether improving sleep quality also accelerates motor function, offering insights for clinicians on the most effective interventions. Conventional approaches—such as cognitive behavioural therapy for insomnia (CBTi), sleep medications, and sleep hygiene practices —provide a strong foundation for treatment. For stroke patients with obstructive sleep apnoea (OSA), continuous positive airway pressure (CPAP) therapy represents an additional conventional approach, with evidence suggesting its potential to improve both sleep quality and recovery outcomes (Tomfohr *et al.*, 2012). Furthermore, a personalised approach, tailored to address specific issues found through detailed sleep assessments, could make these therapies more effective.

Cognitive Behavioural Therapy for Insomnia (CBT-I) is recognised as the first-line treatment for chronic insomnia. It has demonstrated effectiveness across a broad range of populations (Trauer et al., 2015; Herron et al., 2018; Nguyen et al., 2019). However, in individuals who have experienced a stroke, adaptations to the standard CBT-I protocol are often necessary. This is due to common post-stroke challenges such as cognitive impairments, fatigue, reduced mobility, and communication difficulties. Although there is limited literature specifically addressing the use of CBT-I in stroke survivors, evidence from related neurological populations, especially those with traumatic brain injury (TBI), suggests that CBT-I remains both feasible and effective when appropriately modified (Fleming et al., 2024).

Key adaptations include simplifying the language used, incorporating visual aids, and shortening session durations. These modifications help accommodate attention and memory limitations. For individuals with expressive or receptive aphasia, structured content delivery and the involvement of carers or therapists trained in supported communication strategies are recommended. In addition, the increasing use of digital and telehealth platforms in stroke rehabilitation has improved the accessibility of CBT-I. This enables therapist-guided, home-based delivery (Smejka et al., 2022; Sweetman, Reynolds and Richardson, 2024).

Although stroke-specific adaptations are still underrepresented in the literature, modifications drawn from TBI studies may be transferable. This is due to the pathophysiological similarities between stroke and TBI. For example, Hoge et al. (2008) identified several barriers affecting CBT-I effectiveness in individuals with TBI, many of which are also observed in stroke populations.

The following sections outline these challenges and the corresponding adaptations (Almklov, Rivera and Orff, 2022).

Cognitive deficits: TBI often affects attention, memory, and executive function (Testa et al., 2006; Barker-Collo et al., 2015). To address these issues in CBT-I, simplified content, repetition, and memory aids can be used. Tools like CogSMART may support cognitive engagement (Twamley et al., 2014; Cassidy-Eagle et al., 2018). Sleep apps can be helpful when diary compliance is poor.

Pain symptoms: Chronic pain is common after TBI and may worsen alongside insomnia or post-traumatic stress (Nampiaparampil, 2008; Balba et al., 2018). CBT-I can be adapted by combining it with mindfulness strategies, Acceptance and Commitment Therapy (ACT), and supportive routines such as optimising medication timing or bedding comfort (Almklov, Rivera and Orff, 2022).

Mental health conditions: Depression, anxiety, and PTSD frequently co-occur with TBI (Bryant et al., 2010; Whelan-Goodinson et al., 2010). Integrating CBT-I with trauma-focused therapies or CBT for mood disorders can enhance outcomes for both sleep and mental health. Selective serotonin reuptake inhibitors (SSRIs) and imagery techniques may also provide additional support (Fann, Hart and Schomer, 2009; Soo and Tate, 2007).

5.3.4 Optimising the Inpatient Environment for Better Sleep

In this study, participants were community-dwelling, mostly chronic stroke patients, which may explain why significant differences in motor function were only observed for one fluency metric between the two sessions. Nevertheless, significant relationships between sleep and motor function variables imply the importance of addressing sleep problems for stroke recovery. While sleep problems should be addressed at all stages of stroke recovery, particular emphasis should be placed on the acute phase, as neuroplasticity is most active during this period, and the majority of recovery occurs within the first six months post-stroke (Hara, 2015; Dąbrowski *et al.*, 2019).

Stroke patients in the early acute phase are often hospitalised, making post-stroke care—including medical treatment and rehabilitation services—essential in shaping their sleep quality during their hospital stay. Moreover, sleep disturbances are commonly reported among adults in the acute recovery phase (Iddagoda *et al.*, 2020; Miano *et al.*, 2022), and research indicates that poor sleep patterns, particularly short sleep duration (<7 hours), persist for many patients from admission to discharge (Williams-Cooke *et al.*, 2021). These disturbances arise from both primary factors, like stroke-induced disruptions in the brain's sleep centres, and secondary factors, including anxiety, pain, and physical inactivity (Xie, Kang and Mills, 2009; Bakken *et al.*, 2012; Buxton *et al.*, 2012; Allen *et al.*, 2013) environmental conditions (such as lighting, temperature, and noise), and interruptions from

medical routines or staff interactions (Yelden *et al.*, 2015; Grossman *et al.*, 2017; Tan *et al.*, 2019).

Environmental factors can be controlled by simple measures: A comprehensive review of nonpharmacologic sleep interventions for older inpatients found that basic measures, like earplugs and eye masks, could enhance sleep quality (Johnson, Shipper and Westlake, 2019). A UK-based randomised trial with 206 patients in medical and surgical wards supported this, showing improved sleep quality with earplug and eye mask use. However, these interventions did not affect other outcomes, such as fall rates or length of stay (Sweity *et al.*, 2019). Additionally, research by West *et al* (2019) examined the impact of naturalistic lighting in an inpatient stroke rehabilitation unit and found that while subjective sleep quality measured by PSQI did not improve significantly, patients reported feeling "fresh and rested" upon waking, suggesting potential benefits for both sleep and reduced fatigue.

Given the significant role that sleep plays in neuroplasticity (Catherine F. Siengsukon and Boyd, 2009; Couyoumdjian *et al.*, 2010), hospitals should consider personal, environmental, and healthcare system factors to optimise sleep quality (Williams-Cooke *et al.*, 2021). These measures will be crucial in supporting stroke patients' recovery and maximising the benefits of rehabilitation.

5.3.5 Integrating Sleep into Stroke Rehabilitation

The correlation observed between sleep and motor function in this study suggests that sleep should be actively considered and monitored within rehabilitation settings, as it supports neuroplasticity, memory, and motor learning (Catherine F. Siengsukon and Boyd, 2009; Couyoumdjian *et al.*, 2010; Al-Sharman and Siengsukon, 2014), Given that effective rehabilitation is necessary for patients to learn or re-learn activities necessary for daily life, exploring sleep as a contributing factor in the rehabilitation process may offer valuable insights (Frange, Murray and Coelho, 2023).

Specifically, Physical therapists should consider incorporating sleep hygiene practices into their rehabilitation strategies to improve both sleep quality and duration (Frange, Murray and Coelho, 2023). Routine sleep assessments should be conducted during stroke evaluations to identify and address any sleep issues that may affect recovery. By

recognising the importance of sleep in the rehabilitation process, healthcare providers can better support stroke patients in achieving optimal recovery outcomes.

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Appendices

Appendix 1 - Search Strings Used for Systematic Literature Review

EMBASE

1. exp brain hemorrhage/
2. exp brain ischemia/
3. exp cerebrovascular accident/
4. intracranial hemorrhage*.ti,ab.
5. hemipleg*.ti,ab.
6. hemipares*.ti,ab.
7. cva.ti,ab.
8. cerebrovascular accident.ti,ab.
9. stroke.ti,ab.
10. exp sleep/
11. exp sleep disorder/
12. exp sleep deprivation/
13. insomnia*.ti,ab.
14. hypersomnia*.ti,ab.
15. Parasomnia*.ti,ab.
16. Dyssomnia*.ti,ab.
17. Circadian rhythm.ti,ab.
18. sleep*.ti,ab.
19. exp physical medicine/
20. exp neurorehabilitation/
21. exp rehabilitation medicine/
22. exp exercise/
23. recover*.ti,ab.
24. rehab*.ti,ab.
25. physiotherap*.ti,ab.
26. physical therap*.ti,ab.
27. exercise*.ti,ab.
28. walk*.ti,ab.
29. gait.ti,ab.
30. exp walking/
31. 1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9
32. 10 or 11 or 12 or 13 or 14 or 15 or 16 or 17 or 18
33. 19 or 20 or 21 or 22 or 23 or 24 or 25 or 26 or 27 or 28 or 29 or 30
34. 31 and 32 and 33
35. limit 34 to (english or turkish)
36. nonhuman/
37. 35 not 36
38. review.pt.
39. editorial.pt.
40. letter.pt.
41. erratum.pt.
42. conference abstract.pt.
43. chapter.pt.
44. short survey.pt.
45. tombstone.pt.
46. or/38-45

47. 37 not 46

MEDLINE

1. exp stroke/
2. exp brain Ischemia/
3. exp intracranial hemorrhages/
4. hemipleg*.ti,ab.
5. cva.ti,ab.
6. cerebrovascular accident.ti,ab.
7. stroke.ti,ab.
8. hemipares*.ti,ab.
9. intracranial hemorrhage*.ti,ab.
10. cva.ti,ab.
11. exp sleep/
12. exp sleep wake disorders/
13. exp Circadian Rhythm/
14. insomnia*.ti,ab.
15. hypersomnia*.ti,ab.
16. Parasomnia*.ti,ab.
17. Dyssomnia*.ti,ab.
18. Circadian rhythm.ti,ab.
19. sleep*.ti,ab.
20. exp Rehabilitation/
21. exp Exercise/
22. exp Gait/
23. recover*.ti,ab.
24. rehab*.ti,ab.
25. physiotherap*.ti,ab.
26. physical therap*.ti,ab.
27. exercise*.ti,ab.
28. walk*.ti,ab.
29. gait.ti,ab.
30. 1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9 or 10
31. 11 or 12 or 13 or 14 or 15 or 16 or 17 or 18 or 19
32. 20 or 21 or 22 or 23 or 24 or 25 or 26 or 27 or 28 or 29
33. 30 and 31 and 32
34. limit 33 to (english or turkish)
35. review.pt.
36. editorial.pt.
37. 35 or 36
38. 34 not 37

CINAHL

#	Query	Action
S38	S36 NOT S37	472

S37	MH ANIMALS+	96,367
S36	S34 NOT S35	480
S35	PT review	317,920
S34	S27 AND S29 AND S32	516
S33	S27 AND S29 AND S32	Display
S32	S28 OR S31	Display
S31	parasomnia*	Display
S30	S27 AND S28 AND S29	Display
S29	S17 OR S18 OR S19 OR S20 OR S21 OR S22 OR S23 OR S24 OR S25 OR S26	Display
S28	S10 OR S11 OR S12 OR S13 OR S14 OR S15 OR S16	Display
S27	S1 OR S2 OR S3 OR S4 OR S5 OR S6 OR S7 OR S8 OR S9	Display
S26	gait	EditS26
S25	walk*	Display
S24	exercise*	Display
S23	physical therap*	Display
S22	physiotherap*	Display
S21	rehab*	Display
S20	recover*	Display
S19	(MH “Exercise+”)	Display
S18	(MH “Movement+”)	Display
S17	(MH “Rehabilitation+”)	Display
S16	Dyssomnia*	Display
S15	Insomnia*	Display
S14	Hypersomnia*	Display
S13	"circadian rhythm"	Display
S12	sleep*	Display
S11	(MH "Sleep Disorders+")	Display
S10	(MH "Sleep+")	Display
S9	stroke	Display
S8	intracranial hemorrhage*	Display
S7	hemipleg*	Display

S6	hemipares*	Display
S5	cva	Display
S4	cerebrovascular accident	Display
S3	(MH "Stroke+")	Display
S2	(MH "Cerebral Ischemia+")	Display
S1	(MH "Intracranial Hemorrhage+")	

CENTRAL

ID	Search
#1	MeSH descriptor: [Stroke] explode all trees
#2	MeSH descriptor: [Brain Ischemia] explode all trees
#3	MeSH descriptor: [Intracranial Hemorrhages] explode all trees
#4	"CEREBROVASCULAR ACCIDENT"
#5	CVA
#6	HEMIPLEG*
#7	STROKE
#8	HEMIPARES*
#9	"INTRACRANIAL HEMORRHAGE*"
#10	#1 OR #2 OR #3 #4 OR #5 OR #6 OR #6 OR #7 OR #8 OR #9
#11	MeSH descriptor: [Sleep] explode all trees
#12	MeSH descriptor: [Sleep Wake Disorders] explode all trees
#13	MeSH descriptor: [Circadian Rhythm] explode all trees
#14	INSOMNIA*
#15	HYPERSOMNIA*
#16	PARASOMNIA*
#17	DYSSOMNIA*
#18	"CIRCADIAN RHYTHM"
#19	SLEEP*
#20	#11 OR #12 OR #13 #14 OR #15 OR #16 OR #17 OR #18 OR #19
#21	MeSH descriptor: [Rehabilitation] explode all trees
#22	MeSH descriptor: [Exercise] explode all trees
#23	MeSH descriptor: [Gait] explode all trees
#24	RECOVER*
#25	REHAB*
#26	PHYSIOTHERAP*
#27	PHYSICAL THERAP*
#28	EXERCISE*
#29	WALK*
#30	GAIT
#31	#21 OR #22 OR #23 #24 OR #25 OR #26 OR #27 OR #28 OR #29 OR #30
#32	#10 AND #20 AND #31

Appendix 2 - Ethics Approval

Faculty of Medicine and Health Sciences Research Ethics Committee

University of East Anglia

Prof Valerie Pomeroy
School of Health Sciences
University of East Anglia
Norwich Research Park
Norwich
NR4 7TJ

NORWICH MEDICAL SCHOOL
Bob Champion Research & Educational Building
Rosalind Franklin Road
University of East Anglia
Norwich Research Park
Norwich NR4 7UQ

Email: fmh.ethics@uea.ac.uk
www.med.uea.ac.uk

26th November 2020

Dear Val

Project Title: Relationship between neuromuscular recovery, functional ability and sleep after stroke, and, criterion validity of measures made by the Vicon and Biokido motion analysis systems

Reference: 2020/21-028

Your resubmission was considered by the Faculty Research Ethics Committee at their meeting on 26th November 2020 and I can confirm that your proposal has been approved.

Please can you ensure that any amendments to either the protocol or documents submitted are notified to us in advance, and that any adverse events which occur during your project are reported to the Committee.

Approval by the FMH Research Committee should not be taken as evidence that your study is compliant with GDPR and the Data Protection Act 2018. If you need guidance on how to make your study GDPR compliant, please contact your institution's Data Protection Officer.

Please could you also arrange to send us a report once your project is completed.

Yours sincerely

Dr Jackie Buck
Chair
FMH Research Ethics Committee

COVID-19: The FMH Research Ethics Committee procedures remain as normal. Please note that our decisions as to the ethics of your application take no account of changes in Government measures and UEA guidelines relating to the coronavirus pandemic and all approvals granted are, of course, subject to these.

Appendix 3 - Ethics Amendments Approval

Ethics ETH2122-1583 (Significant amendments): Prof Valerie Pomeroy

Date Created	21 Mar 2022
Date Submitted	21 Mar 2022
Researcher	Prof Valerie Pomeroy
	Miss Canan Yuksel
	Miss Merve Kizilay
	Miss Elizabeth Chandler
	Dr Allan Clark
	Dr Nicola Hancock
	Mr David Payne
	Dr Alpar Lazar
Category	Staff
	Staff
	PGR
	Staff
	Staff
	Staff
	Staff
	Staff
Faculty	Faculty of Medicine & Health Sciences
Department	FMH Faculty Professional Services
Current status	Approved

Ethics application

Applicant and research team

Principal Applicant

Name of Principal Applicant
Prof Valerie Pomeroy

UEA account
hsv07fyu@uea.ac.uk

School/Department
School of Health Sciences

Category
Staff

Co-applicant(s) at UEA

Name of Co-applicant at UEA where applicable

Miss Canan Yuksel

Miss Merve Kizilay

Miss Elizabeth Chandler

Dr Allan Clark

Dr Nicola Hancock

Mr David Payne

Dr Alpar Lazar

Co-applicant's school/department

School of Health Sciences; School of Health Sciences; School of Health Sciences; Norwich Medical School; School of Health Sciences; FMH Faculty Professional Services; School of Health Sciences

External Co-applicant(s)

Name of external Co-applicant where applicable.

Louise Gilbert

Name of external Co-applicant's organisation/institution where applicable.

Norfolk Community Health & Care NHS Trust

Project details

Project title

Developing measurement of movement performance using

the “gold-standard” Vicon and novel Biokido motion analysis systems:

normal values, test-retest reliability, criterion validity and smallest detectable difference

Project start date.

24 Feb 2020

Project end date.

31 Aug 2021

Is the project?:

none of the options listed

Original application and ethics approval

Original UEA ethics review body.

FMH S-REC (Faculty of Medicine and Health Sciences Research Ethics Subcommittee)

Original UEA ethics application reference number.
2019/20-044

Original approved ethics application.
Original ethics approval letter/email.

Amendment type

Type of amendment
Change to project end date
Change to research protocol

Is this amendment related to Covid-19?
No

Change project end date

Original project end date
31 Aug 2021

Revised project end date
30 Sept 2022

Explain why your anticipated project end date has changed.
am pleased to report that the above study is proceeding well now that the COVID-19 pandemic has lessened. However, data processing has revealed that we will not have the required 54 complete data sets by the time we have reached our current recruitment target of up to 65 participants. I am therefore seeking approval of the FMH Ethics committee to increase our target recruitment to 'up to 75 participants'. As we are processing data within two/three days of collection in the MoveExLab I anticipate that the actual recruitment will be less than 75 people to provide the required 54 data sets. However, I request 'up to 75 participants' to avoid returning with another request later.

Also, I will be grateful if for a check of the current end data of this project. I fear that with the amendments to process during the COVID period, agreed by FMH Ethics, that we may have lost sight of extending the end date for data collection. I estimate generously that this will now be 20th September 2022.

Attach any documentation which relates to the changes described.

Change research protocol

Fully describe any changes and upload revised documentation if there are wording changes to the original application.
I am pleased to report that the above study is proceeding well now that the COVID-19 pandemic has lessened. However, data processing has revealed that we will not have the required 54 complete data sets by the time we have reached our current recruitment target of up to 65 participants. I am therefore seeking approval of the FMH Ethics committee to increase our target recruitment to 'up to

75 participants'. As we are processing data within two/three days of collection in the MoveExLab I anticipate that the actual recruitment will be less than 75 people to provide the required 54 data sets. However, I request 'up to 75 participants' to avoid returning with another request later.

Also, I will be grateful if for a check of the current end data of this project. I fear that with the amendments to process during the COVID period, agreed by FMH Ethics, that we may have lost sight of extending the end date for data collection. I estimate generously that this will now be 20th September 2022.

Attach any documentation which relates to the changes described.

University of East Anglia
Norwich Research Park
Norwich. NR4 7TJ

Email: ethicsmonitor@uea.ac.uk
Web: www.uea.ac.uk

Study title: Developing measurement of movement performance using the "gold-standard" Vicon and novel Biokido motion analysis systems: normal values, test-retest reliability, criterion validity and smallest detectable difference

Application ID: ETH2122-1583 (Amendment prior to EM)

Dear Valerie,

Your amendment to your study was considered on 22nd March 2022 by the FMH S-REC (Faculty of Medicine and Health Sciences Research Ethics Subcommittee).

The decision is: **approved**.

You are therefore able to start your project subject to any other necessary approvals being given.

If your study involves NHS staff and facilities, you will require Health Research Authority (HRA) governance approval before you can start this project (even though you did not require NHS-REC ethics approval). Please consult the HRA webpage about the application required, which is submitted through the IRAS system.

This approval will expire on **30th September 2022**.

Please note that your project is granted ethics approval only for the length of time identified above. Any extension to a project must obtain ethics approval by the FMH S-REC (Faculty of Medicine and Health Sciences Research Ethics Subcommittee) before continuing.

It is a requirement of this ethics approval that you should report any adverse events which occur during your project to the FMH S-REC (Faculty of Medicine and Health Sciences Research Ethics Subcommittee) as soon as possible. An adverse event is one which was not anticipated in the research design, and which could potentially cause risk or harm to the participants or the researcher, or which reveals potential risks in the treatment under evaluation. For research involving animals, it may be the unintended death of an animal after trapping or carrying out a procedure.

Any amendments to your submitted project in terms of design, sample, data collection, focus etc. should be notified to the FMH S-REC (Faculty of Medicine and Health Sciences Research Ethics Subcommittee) in advance to ensure ethical compliance. If the amendments are substantial a new application may be required.

Approval by the FMH S-REC (Faculty of Medicine and Health Sciences Research Ethics Subcommittee) should not be taken as evidence that your study is compliant with the UK General Data Protection Regulation (UK GDPR) and the Data Protection Act 2018. If you need guidance on how to make your study UK GDPR compliant, please contact the UEA Data Protection Officer (dataprotection@uea.ac.uk).

Please can you send your report once your project is completed to the FMH S-REC (fmh.ethics@uea.ac.uk).

I would like to wish you every success with your project.

On behalf of the FMH S-REC (Faculty of Medicine and Health Sciences Research Ethics Subcommittee)

Yours sincerely,

Paul Linsley

Appendix 4 – Participant information Sheet for Study 2

University of East Anglia

abira
linking research & practice

Developing measurement of movement performance for use in rehabilitation: normal values, reliability, validity and smallest detectable difference

Information Sheet for potential volunteers

Researchers from the University of East Anglia (UEA) extend an invitation for you to take part in a research project.

We are developing measures of the movement needed for the everyday activity of answering the telephone. Our purpose is to provide new measures that can be used to find out how the brain recovers after stroke and how brain recovery can be improved by physiotherapy. This project will increase knowledge about the movement characteristics of people who have not suffered a stroke. Therefore, this study will provide the reference values needed to improve clinical care of individual stroke survivors.

You do not have to take part if you do not want to.

Talk about the project with others if you would like to.

If you need more information, please ask the researcher, Valerie Pomeroy at UEA. Or get in touch with her personal assistant: Pel Fordham. Both of them will be happy to answer your questions. Their contact information is at the bottom of this page.

Thank you for reading this information sheet and for considering taking part in this project.

Contact Details

Researcher's name: Professor Valerie Pomeroy

Email: v.pomeroy@uea.ac.uk

Phone: 01603 59 1923

Researcher's personal assistant: Pel Fordham

Email: p.fordham@uea.ac.uk

Phone: 01603 59 **1923**

What is the purpose of this project?

There is strong evidence that physiotherapy improves the ability of people to move and be independent after suffering a stroke. But at six months after stroke many people remain unable to produce the movement needed for every-day activity such as picking up a telephone. This situation could be improved by using physiotherapy interventions to aid the recovery of movement after stroke. It is therefore important to be able to recognise if a physiotherapy intervention is aiding movement recovery for stroke survivors to enable them to undertake every-day activity. This requires knowledge of the movement characteristics of people who have not suffered a stroke. This project will provide the required knowledge by using the specialised equipment in the Movement and Exercise Laboratory at the University of East Anglia (MoveExLab).

However, if movement measures are to be used routinely in clinical practice then relying on specialist facilities such as the MoveExLab will not be practical. This equipment is also expensive. So, this project will find out if new equipment, that costs less and is designed for use in small spaces, also provides movement measures that are sensitive to change.

This project will provide the reference values for measures needed in clinical practice to improve movement recovery for stroke survivors. This project will also find out if the movement measures can be made equally as well with new equipment, called Biokido, that is more suitable for use clinically.



Am I eligible to take part in this project?

You are potentially eligible to participate if:

- You are aged 18 or above and
- You do not have or have had an illness that has affected your ability to move e.g.:a painful knee, osteoporosis, multiple sclerosis
- You do not have an allergy to latex

If you are interested, then I (Valerie Pomeroy) would like to talk to you about if you can be involved in this project. My contact details and those of my personal assistant are provided on page 1 of this leaflet.

Do I have to take part?

No, you do not have to take part.

It is entirely up to you to decide. If you would prefer not to take part, that is OK. If you do take part, **you may withdraw at any time without giving a reason.**

If you do withdraw, we can only destroy your data up to the point they are anonymised. After that point, it will not be possible to separate your data.

What will I have to do if I am interested?

If you are able to take part in the project, then we will invite you to attend the Movement and Exercise Laboratory at the University of East Anglia (MoveExLab) for some assessments at a time of your convenience. All necessary travel will be reimbursed, and pre-paid taxis can be arranged if you wish us to do so.

What will I have to do if I take part?

You will be invited to undertake two assessments at the MoveExLab. These assessments will be between 1 and 4 weeks apart depending on your preference. The assessments will take **around 1 hour** to complete at **the MoveExLab** (picture on right of this paragraph). Y**ou may stop at any time**.

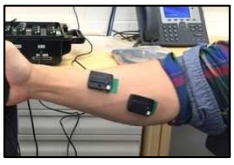


First: We will ask you to **fill in a form** to gather demographic data. We will also ask questions about any allergies you have to ensure that you are unlikely to have any reactions from sticky tape and other materials in the MoveExLab. If you do have allergies, e.g. to sticky tape, then we can adjust the materials we use for testing or aspects of the MoveExLab environment. However, if you have an allergy to latex then we are unable to make adjustments and you will be unable to take part.

Second: We will ask you to change into shorts and a sleeveless T-shirt in a curtained-off private changing area. You can bring your own clothing, or you can use the MoveExLab clothing which is freshly laundered for each participant. You can decide. We will also ask you to take off your shoes and socks.

We will then measure your height and weight. Then we will measure your body size e.g. the width of your hands and length of your legs. These measurements are needed by the motion analysis software to produce the movement measures.

Third: We will place electromyography (EMG) electrodes on your skin using hypoallergenic sticky tape. These EMG electrodes will measure your muscle activity as you move. The picture on the right shows the EMG electrodes in place. These EMG electrodes do not hurt. They just record your natural muscle activity during movement.



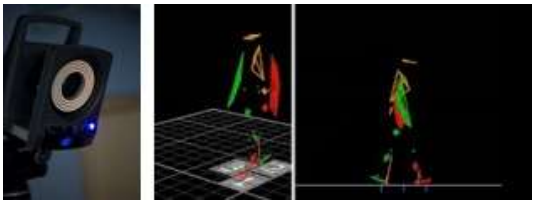
We will also place reflective markers on your skin using hypoallergenic sticky tape. These reflective markers are tracked by infra-red cameras placed at the top of the walls of the MoveExLab. On the right of this text is a picture to illustrate these reflective markers in place. These markers do not hurt. They just record movement of your body.



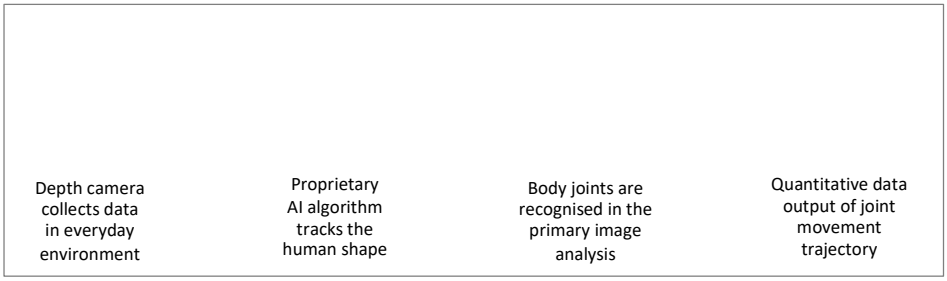
Fourth: As part of this study we will use electroencephalography (EEG). EEG measures the electrical activity of the brain using electrodes (small metal discs or sensors) which are mounted on a cap and placed on the head with gel. The EEG cap does not hurt, and the entire procedure usually takes about 15 minutes. The gel used to put the sensors on the head can sometimes be slightly sticky and the EEG cap in rare instances may cause slight discomfort.



Fifth: You will be asked to stand still in the middle of the MoveExLab. The eight infra-red cameras placed around the top of the walls will record the light signals from the reflective markers on your body. The motion analysis software will then use the collected information to calibrate your body in the space in which you are going to move. Placed at the right of this paragraph is a photograph of one infra-red camera and examples of the 'pictures' of movement captured.



Your movement will also be 'captured' by a new motion analysis system called the Biokido Motion Analysis system. The Biokido motion analysis system is illustrated in the pictures placed at the bottom of this paragraph. The system consists of a depth camera and a portable computer with specialist software. The system is fully portable and can be used in small spaces. Therefore, if the measures made with the Biokido system agree with those made by the MoveExLab system then it may be placed in clinical settings for routine measures that are unable to be made now.



Sixth: You will be seated with a telephone placed on a table 3 metres in front of you. Your task will be to go and answer the telephone when you hear a buzzer. You will be instructed in exactly what to do and given time to practice. When you are confident in doing this task, we will record your movement and muscle activity whilst you do it. You will repeat this task until the technician tells you that there are 5 trials which have reconstructed well on the computer. Please note that most trials reconstruct well so it is unlikely that you will have to

do this task more than 5 times. The maximum number of times we will ask you to complete this task will be ten if there are problems with computer reconstruction.

Seventh: You will stay seated and we will bring the table in front of you so that you can rest your forearm on it. Your task will be to answer the telephone placed directly in front of you, with your dominant hand, when you hear the buzzer. You will be instructed in exactly what to do and given time to practice. When you are confident in doing this task, we will record your movement and muscle activity whilst you do it. You will repeat this task until the technician tells you that there are 5 trials which have reconstructed well on the computer. Then you will do another 5 trials with the telephone on the left of the table. Followed by 5 trials with the telephone on the right of the table. Please note that most trials reconstruct well so it is unlikely that you will do more than 15 trials of this task. The maximum number of times we will ask you to complete this task will be 30 if there are problems with computer reconstruction.

Eighth: We will remove the EEG cap, EMG electrodes and reflective markers that were placed on your skin. The sticky tape is similar to a sticking plaster. Most people do not experience any discomfort. You will then change back into your normal clothes in the curtained-off private changing area.

The assessment is then completed.

What will happen to my information?

Information will include your **age, gender and ethnicity**.

We will also store personal information such as your **telephone number** and/or **email address** so that we may **arrange your appointment** with us.

Your contact details will be **stored safely.**

Personal information will not be associated with the results in any way.

You will be given a project number for the purpose of collecting and analysing data. This means you **will remain anonymous.**

The data will be **accessible only by authorised people** within the research team. Who must **follow strict ethical protocols** in the **handling and storage** of all project **data** and observe the **General Data Protection Regulation** (2018).

What if I want to take part in future research?

The consent form also has an option to take part in **further research**. **You do not have to tick this.**

If you want to be involved with future stroke rehabilitation research, your name and contact details will be available on a **secure database accessible only by members of the Acquired Brain Injury Rehabilitation Alliance** (ABIRA) here at UEA. **You can withdraw from this database at any point**.

Will my taking part in this project be kept confidential?

All data will be **anonymised so that your name will not be used in any records** made in connection with the project.

The only time that **we would pass on identifiable information** would be if **you disclosed information of a serious incident** or information that made us think that **you or someone else, was at risk of serious harm**.

If during analysis of your movement data, we identify a movement difficulty then the research team will advise you to visit your GP for medical advice.



How will my information be stored?

Fully anonymised **data** will be **stored** securely in the **research office and on password-protected computers** during the project.

Long-term data is then stored in a secure room on a password protected computer at **UEA** for **10 years after the end of the project**. After the 10 years the anonymised database will be retained on the servers of UEA for any required analysis.

All procedures for the handling, processing, storage and destruction of data are **compliant with the General Data Protection Regulation** (2018)



What will happen to the results of the research project?

The results of the project will be used to inform a subsequent investigation of the usefulness of movement measures for stroke survivors.

The anonymised results will be presented at scientific conferences, professional meetings and t scientific seminars. Anonymised results will also be published in scientific journals.

The anonymised results will also be available to participants who took part in the project and the general public by placement of the ABIRA website, the UEA website and on social media. Again, no participants will be identifiable.

The anonymised results will also form part of the PhD theses of two research students who are involved in this project.

Are there any possible risks with this project?

There are no know risks associated with taking part in this project.

What are the possible benefits of taking part?

The data we obtain from your participation will provide new knowledge about how to make measures of movement needed for every-day tasks. We do not anticipate any direct benefits for participants in this project.

We greatly appreciate the contribution of participants to this research and to future potential research which, we hope, will benefit stroke survivors

What if there is a problem?

If you have **any complaints** about the way you have been dealt with or any harm is caused during the project **this will be addressed**.

You can **contact the researchers** at any point (whose information is at the beginning of this sheet).

What if I no longer wish to continue with the project?

You may withdraw from the project **at any time** without giving a reason.

Who has reviewed this project?

This project has been reviewed extensively by experts in the research team and has been granted ethical approval by the Ethical Committee of the UEA Faculty of Medicine and Health who protect the dignity, rights, safety and well-being of participants and researchers.

Who is organising this project?

This project is organised by UEA and the Acquired Brain Injury Research Alliance (ABIRA) and is in collaboration with the creators of the Biokido motion analysis system

Thank you for taking the time to read this leaflet.

If you choose to participate, you will keep a copy of this participant information sheet and the signed informed consent form

Appendix 5 – Consent from for Study 2

Date of visit |__|__|-|__|__|-|__|__|__|__| (DD-MM-YYYY)

University of East Anglia

Participant Identification Number: | _____|

Developing measurement of movement performance for use in rehabilitation:
normal values, reliability, validity and smallest detectable difference

Consent Form for volunteers

Name of Researcher: _____

Name of Participant: _____

Participant Identification Number: | _____|

	Please initial the box
I have read and understood the participant information sheet (PIS Version 3, 6 January 2020)	
I understand that I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily	
I understand that my participation is voluntary and that I am free to withdraw at any time until the point that my data are anonymised without giving any reason.	
I agree to complete a form to provide asking for: my demographic information (e.g., age, sex) and information about any allergies of relevance to this project.	
I understand that I will attend the MoveExLab at the University of East Anglia on two separate occasions and that any necessary travel expenses will be reimbursed.	
I understand that I will undertake assessments for measurement of my muscle activity and my movement at the MoveExLab at the University of East Anglia.	
I understand that while information gained during the study may be published, I will not be identified and all information (demographic, muscle activity and movement) will be anonymised.	
I agree to take part in the study.	

	Please initial the appropriate box	
I agree to my name and contact details being held on a secure database at the University of East Anglia so that I can be contacted regarding follow-up to this study and opportunities for future research that has been ethically approved.	YES	NO
I agree for my anonymised data captured with the Biokido system to be sent to the manufacturer in Turkey so that it can be analysed. I understand that my anonymised data will be in blurred pictorial format as in the illustration of the Biokido system in the information sheet. My data transferred to Turkey for analysis will only be identifiable by the anonymised study number.		

Name of participant	
Signature	
Date	

Name of person taking consent	
Signature	
Date	

One original copy of this form should be completed. The original should be stored in the investigator site file. Photocopies should be made of the original and given to the participant

Appendix 6 – Recruitment advertisement for Study 2

Brain recovery after stroke is puzzle

Would like to be part of the solution?

We are developing new measures of movement to find out how the brain recovers after stroke. We need healthy people to compare the measures. All you need to do is move from a chair to answer a telephone while we record your movement.

In detail, we are recruiting adults who do not have any neurological or musculoskeletal condition impacting on their ability to move or have a latex allergy. This project will involve measuring your movement whilst you undertake the every-day task of picking up a telephone several times. To measure your movement, we will stick small reflective markers and sensors on your skin. No painful or intrusive methods are used. You will need to attend two 60-minute sessions in the Movement and Exercise Laboratory at the University of East Anglia.

For more information click the link: http://www.abira.ac.uk/projects/developing-new-measures-of-movement-ability-to-improve-personalisation-of-therapy-for-stroke-survivors/

Contact with v.pomeroy@uea.ac.uk & p.fordham@uea.ac.uk

Appendix 7 – Participant Information Sheet for Study 3

University of East Anglia

abira
linking research & practice

Relationship between neuromuscular recovery, functional ability and sleep after stroke, and, criterion validity of measures made by the Vicon and Biokido motion analysis systems

Information Sheet for potential volunteers

Researchers from the University of East Anglia (UEA) extend an invitation

for you to take part in a research project.

We are investigating how physiotherapy can be directed at the biological underpinnings of movement to improve recovery after stroke. These biological underpinnings are called neuromuscular function. Neuromuscular function includes: the ability to use weak muscles in the right order and at the right time during movement and performing everyday tasks such as answering the telephone in the same way as you did before the stroke. Also being investigated is whether sleep patterns may influence recovery of neuromuscular function

We are also developing measures of the movement needed for the everyday activity of answering the telephone. Our purpose is to provide new measures for finding out how the brain recovers after stroke and how physiotherapy may be focused at the biological underpinnings of movement recovery after stroke.

You do not have to take part if you do not want to.

Talk about the project with others if you would like to.

If you need more information, please ask the researcher, Valerie Pomeroy at UEA. Or get in touch with her personal assistant: Pel Fordham. Both of them will be

happy to answer your questions. Their contact information is at the bottom of this page.

Thank you for reading this information and for considering taking part in this project.

Contact Details
Researcher's name: Professor Valerie Pomeroy **Email:** v.pomeroy@uea.ac.uk **Phone:** 01603 59 1923 **Researcher's personal assistant:** Pel Fordham **Email:** p.fordham@uea.ac.uk **Phone:** 01603 59 **1923** **School of Health Sciences, Queen's Building, University of East Anglia, Norwich Research Park, Norfolk, NR4 7TJ**

What is the purpose of this project?

There is strong evidence that physiotherapy improves the ability of people to move and be independent after suffering a stroke. But at six months after stroke many people remain unable to produce the movement needed for every-day activity such as answering a telephone. This situation could be improved by using physiotherapy interventions to aid the recovery of movement after stroke and changing an individual's sleep pattern. It is therefore important to be able to recognise if a physiotherapy intervention is aiding movement recovery for stroke survivors to enable them to undertake every-day activity. This requires a deeper knowledge of the biological underpinnings of movement called neuromuscular function. This project will provide the required knowledge by using the

specialised equipment in the Movement and Exercise Laboratory at the University of East Anglia.

However, if movement measures are to be used routinely in clinical practice then relying on specialist facilities such as the Movement and Exercise Laboratory (MoveExLab) will not be practical. This equipment is expensive and can only be used in large specialised laboratories So, this project will find out if new equipment, that costs less and is designed for use in small spaces, also provides movement measures that are sensitive to change. This is important as most stroke rehabilitation takes place in people's own homes.

This project will identify the aspects of neuromuscular function that may be targeted by physiotherapy treatment to improve movement recovery. It will also inform knowledge of the sleep patterns that are beneficial for movement recovery after stroke. This project will also find out if the movement measures can be made equally as well with new equipment, called Biokido, that is more suitable for use in everyday routine rehabilitation.

Am I eligible to take part in this project?

You are potentially eligible to participate if:



- You are aged 18 or above and
- You have had a stroke at any point in the past
- You are discharged from NHS stroke services
- You do not have an allergy to latex

If you are interested, then I (Valerie Pomeroy) would like to talk to you about if you can be involved in this project. My contact details and those of my personal assistant are provided on page 1 of this leaflet.

Do I have to take part?

No, you do not have to take part.

It is entirely up to you to decide. If you would prefer not to take part, that is OK. If you do take part, **you may withdraw at any time without giving a reason.**

If you do withdraw, we can only destroy your data up to the point they are anonymised. After that point, it will not be possible to separate your data.

What will I have to do if I am interested?

If you are able to take part in the project, then we will invite you to attend the Movement and Exercise Laboratory at the University of East Anglia (MoveExLab) for some assessments at a time of your convenience. All necessary travel will be reimbursed up to a maximum of a 50-mile return journey. We can arrange a pre-paid taxi return journey if you wish us to do so. Other than reimbursement of travel expenses there is no payment for taking part in this project.

What will I have to do if I take part?



You will be invited to undertake two assessments at the MoveExLab. These assessments will be between 2 and 4 months apart depending on your preference. The assessments will take **around 90 minutes** to complete at **the MoveExLab** (picture on right of this paragraph). Y**ou may stop at any time**. **Some of the measures are undertaken by you in your own home.**

We have put in place additional procedures to **keep you and us as safe as possible during the COVID-19 pandemic**. Before you arrive at the MoveExLab we will send you an additional information sheet and the URL to a video explaining the additional procedure that meets the requirements of our UEA-approved risk assessment. The **additional information is provided for you as an appendix at the end of this project information sheet**. **The**

video can be viewed using this link: http://www.abira.ac.uk/about-abira/research-facilities/**.** Both the COVID-19 information sheet and video have received ethical approval by the UEA Faculty of Medicine and Health Sciences Ethical Committee.

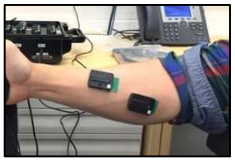
When you arrive at the MoveExLab to undertake the assessment session you will undertake activities in the following order. You will have **rest periods as and when you need them**.

First: We will ask you to **fill in a form** to gather demographic data. We will also ask questions about any allergies you have to ensure that you are unlikely to have any reactions from sticky tape and other materials in the MoveExLab. If you do have allergies, e.g. to sticky tape, then we can adjust the materials we use for testing or aspects of the MoveExLab environment. However, if you have an allergy to latex then we are unable to make adjustments and you will be unable to take part.

Second: We will ask you to change into shorts and a sleeveless T-shirt in a curtained-off private changing area. This clothing is freshly laundered at 60°C for each participant. We will also ask you to take off your socks. You keep your shoes on. The shoes you need to wear are a walking shoe (not hiking boot) or a trainer without reflective strips. You will need to wear the same shoes for both of your visits to the MoveExLab.

We will then measure your height and weight. Then we will measure your body size e.g. the width of your hands and length of your legs. These measurements are needed by the motion analysis software to produce the movement measures.

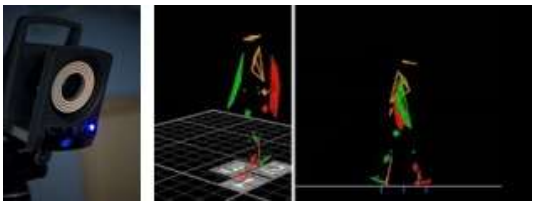
Third: We will place electromyography (EMG) electrodes on your skin using hypoallergenic sticky tape. These EMG electrodes will measure your muscle activity as you move. The picture on the right shows the EMG electrodes in place. These EMG electrodes do not hurt. They just record your natural muscle activity during movement.



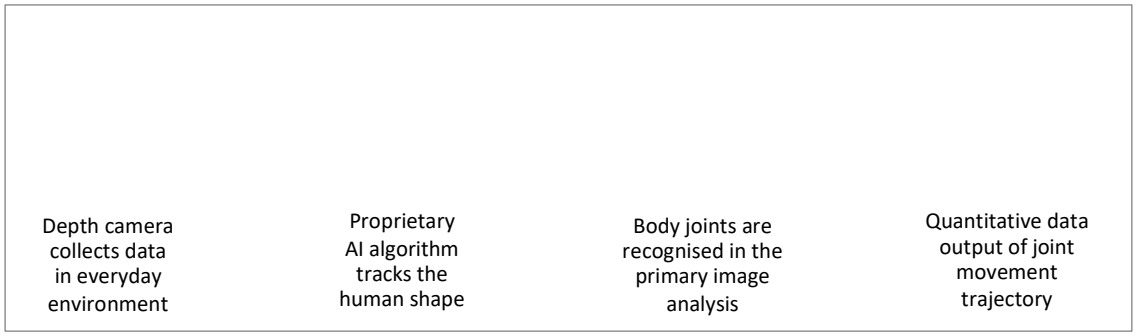
We will also place reflective markers on your skin using hypoallergenic sticky tape. These markers are tracked by infra-red cameras placed at the top of the walls of the MoveExLab. On the right of this text is a picture to illustrate these reflective markers in place. These markers do not hurt. They just record movement of your body.



Fourth: You will be asked to stand still in the middle of the MoveExLab. You will have support if you need it. The eight infra-red cameras placed around the top of the walls will record the light signals from the reflective markers on your body. The motion analysis software will then use the collected information to calibrate your body in the space in which you are going to move. Placed at the right of this paragraph is a photograph of one infra-red camera and examples of the 'pictures' of movement captured.



Your movement will also be 'captured' by a new motion analysis system called the Biokido Motion Analysis system. The Biokido motion analysis system is illustrated in the pictures placed at the bottom of this page. The system consists of a depth camera and a portable



computer with specialist software. The system is fully portable and can be used in small spaces. Therefore, if the measures made with the Biokido system agree with those made by the MoveExLab system then it may be placed in clinical settings for routine measures that are unable to be made now.

Fifth: **You will be seated with a telephone placed on a table 3-metres in front of you. Your task will be to go and answer the telephone when you hear a buzzer.** You will be instructed in exactly what to do and given time to practice. When you are confident in doing this task, we will record your movement and muscle activity whilst you do it. You will repeat this task until the technician tells you that there are 10 trials which have reconstructed well on the computer. Please note that most trials reconstruct well so it is unlikely that you will have to do this task more than 10 times. The maximum number of times we will ask you to complete this task will be 15 if there are problems with computer reconstruction. And

please be assured that if you become tired that you will be provided with sufficient rest time between trials or we will reduce the number of trials for you.

Sixth: **You will stay seated and we will bring the table in front of you so that you can rest your forearm on it. Your task will be to answer the telephone placed directly in front of you, with your weaker hand, when you hear the buzzer**. You will be instructed in exactly what to do and given time to practice. When you are confident in doing this task, we will record your movement and muscle activity whilst you do it. You will repeat this task until the technician tells you that there are 10 trials which have reconstructed well on the computer. Then you will do another 10 trials with the telephone on the left of the table. Followed by 10 trials with the telephone on the right of the table. Please note that most trials reconstruct well so it is unlikely that you will do more than 10 trials of each part of this task. The maximum number of times we will ask you to complete this task will be 45 if there are problems with computer reconstruction. And please be assured that if you become tired that you will be provided with sufficient rest time between trials or we will reduce the number of trials for you.

Seventh: You will then be seated in a chair at one end of the MoveExLab whilst the researchers move the plinth from the middle of the space. **You will stand up from the chair, get your balance and then be asked to walk forwards** to the other end of the MoveExLab**. You will only walk as far as you can safely without any support** from a walking aid or another person**. If you cannot walk without support, you will not do this assessment.** You will do 10 walks if you can.

Eighth: We will **remove EMG electrodes and reflective markers** that were placed on your skin. The sticky tape is similar to a sticking plaster. Most people do not experience any discomfort. Then you will undertake some **clinical measures** called the Fugl-Meyer Assessment and the Action Research Arm Test. These involve **assessment of your: reflexes, joint mobility and ability to pick up small objects with your weaker hand.**

Ninth: You will then **change back into your normal clothes** in the curtained-off private changing area.

Tenth: Once you have changed back into your normal clothes you will complete some **short questionnaires** to assess: your **mood, how well you sleep, and how active you are each**

day. Please note that **if you are tired** then it is possible for you to **complete many of these questionnaires at home**.

Eleventh: The Researcher will then provide you with a **sleep diary to record how well you sleep each day**. You will **take this home with you**. The Researcher will also **give you two motion watches, one for each wrist**. You will be given an **instruction leaflet** for using the motion watches for a 7-day period. This instruction leaflet is provided as an appendix at the end of this information sheet. You will be provided with a stamped addressed padded envelope to post us the motion watches after the 7-day period.





The assessment is then completed.

The **Researcher will keep in touch with you** by telephone and email **in the time in-between your first and second visits**. **You will also be able to contact the Researcher**. The Researcher will be able to **help you if you have any challenges in using the sleep diary or motion watches**. Also, the Researcher will liaise with you to fix a suitable time for you to attend he MoveExLab for your second visit.

What will happen to my information?

Information will include your **age, gender and ethnicity**.

We will also store personal information such as your **telephone number** and/or **email address** so that we may **arrange your appointments** with us and **keep in contact with you during your period of taking part in this study**.

Your contact details will be **stored safely.**

Personal information will not be associated with the results in any way.

You will be given a project number for the purpose of collecting and analysing data. This means you **will remain anonymous.**

The data will be **accessible only by authorised people** within the research team. Who must **follow strict ethical protocols** in the **handling and storage** of all project **data** and observe the **General Data Protection Regulation** (2018).

What if I want to take part in future research?

The consent form also has an option to take part in **further research**. **You do not have to tick this.**

If you want to be involved with future stroke rehabilitation research, your name and contact details will be available on a **secure database accessible only by members of the Acquired Brain Injury Rehabilitation Alliance** (ABIRA) here at UEA. **You can withdraw from this database at any point**.

Will my taking part in this project be kept confidential?

All data will be **anonymised so that your name will not be used in any records** made in connection with the project.



The only time that **we would pass on identifiable information** would be if **you disclosed information of a serious incident** or information that made us think that **you or someone else, was at risk of serious harm**.

If during the study, we identify a potential health problem then the research team will advise you to visit your GP for medical advice.

How will my information be stored?

Fully anonymised **data** will be **stored** securely in the **research office** (paper versions of forms) **and on password-protected computers** (digital versions of forms) during the project. This includes all forms completed during data collection. These data will only be accessible to the UEA members of the research team (see last page of this leaflet).



Until the end of the project we will store your contact details separately to the fully anonymised data. Your contact details data will be stored **securely on a password-protected secure section of the UEA server**. Contact details data will only be accessible to Professor Pomeroy (Chief Investigator), Canan Yuksel (PhD student) and Merve Kizilay (PhD student). **Your contact details for this project will be kept for one year after completion of the data collection and then destroyed.**

Long-term data will be stored in a secure room on a password protected computer at **UEA** for **10 years after the end of the project**. After the 10 years, only the anonymised database will be retained on the secure servers of UEA for any required analysis.

All procedures for the handling, processing, storage and destruction of data are **compliant with the General Data Protection Regulation** (2018)

What will happen to the results of the research project?

The results of the project will be used to inform subsequent investigations of how to improve the effects of physiotherapy treatment and understand more about how neuromuscular recovery happens after stroke.

The anonymised results will be presented at scientific conferences, professional meetings and scientific seminars. Anonymised results will also be published in scientific journals.

The anonymised results will also be available to participants who took part in the project and the general public by placement of the ABIRA website, the UEA website and on social media. Again, no participants will be identifiable.

The anonymised results will also form part of the PhD theses of two research students who are involved in this project.

Are there any possible risks with this project?

There are no know risks associated with taking part in this project.

What are the possible benefits of taking part?

The data we obtain from your participation will provide new knowledge about how to improve stroke rehabilitation. We do not anticipate any direct benefits for participants in this project.

We greatly appreciate the contribution of participants in this research and to future potential research which, we hope, will benefit stroke survivors in the future.

What if there is a problem?

If you have **any complaints** about the way you have been dealt with or any harm is caused during the project **this will be addressed**.

You can **contact the researchers** at any point (whose information is at the beginning of this sheet).

If you have a complaint about this project please contact: Professor Sally Hardy, Dean of Health Sciences, Queen's Building, University of East Anglia, Norwich Research Park, Norfolk, NR4 7TJ. Tel: 01603 593940. E-mail: S.Hardy@uea.ac.uk

What if I no longer wish to continue with the project?

You may withdraw from the project **at any time** without giving a reason.

Who has reviewed this project?

This project has been reviewed extensively by experts in the research team whose details are provided in the last section of this information sheet. Specifically, the project has been reviewed for clinical relevance, scientific accuracy, medical statistics and practicality. The project has been granted ethical approval by the Ethical Committee of the UEA Faculty of Medicine and Health who protect the dignity, rights, safety and well-being of participants and researchers.

Who is organising this project?

This project is organised by UEA and the Acquired Brain Injury Research Alliance (ABIRA) and is in collaboration with the creators of the Biokido motion analysis system

Who are the team members of this project?

Chief Investigator:

- Professor Valerie Pomeroy, Professor of Neurorehabilitation, School of Health Sciences, University of East Anglia

Investigators:

- Ms Canan Yuksel, PhD student, School of Health Sciences, University of East Anglia
- Ms Merve Kizilay, PhD student, School of Health Sciences, University of East Anglia
- Dr Alpar Lazar, Associate Professor in Dementia and Complexity in Later Life, School of Health Sciences, University of East Anglia
- Dr Nicola Hancock, Lecturer in Physiotherapy, School of Health Sciences, University of East Anglia
- Dr Allan Clark, Senior Lecturer in Medical Statistics, Norwich Medical School, University of East Anglia
- Ms Elizabeth Chandler, Clinical Movement Analyst, School of Health Sciences, University of East Anglia
- Mr Jacob Wells, Research Associate, School of Health Sciences, University of East Anglia
- Mr David Payne, Movement Analysis Research Technician, School of Health Sciences, University of East Anglia
- Ms Louise Gilbert, Specialist Physiotherapist, Early Supported Discharge service (stroke), Norfolk Community Health and Care NHS Trust

Thank you for taking the time to read this leaflet.

If you choose to participate, you will keep a copy of this participant information sheet and the signed informed consent form

Appendix 8 – Consent form for Study 3

Date of first visit |__|__|-|__|__|-|__|__|__|__| (DD-MM-YYYY)



Participant Identification Number: | _____|

Relationship between neuromuscular recovery, functional ability and sleep after stroke, and, criterion validity of measures made by the Vicon and Biokido motion analysis systems

Consent Form for volunteers

Name of Researcher: _____

Name of Participant: _____

Participant Identification Number: | _____| (Researcher use only)

	Please initial the box
1. I have read and understood the participant information sheet (PIS Version 3, February 2021)	
2. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily	
3. I understand that my participation is voluntary and that I am free to withdraw at any time until the point that my data are anonymised without giving any reason.	
4. I agree to complete a form to provide asking for: my demographic information (e.g., age, sex) and information about any allergies of relevance to this project.	
5. I understand that I will attend the MoveExLab at the University of East Anglia on two separate occasions and that any necessary travel expenses will be reimbursed. Up to a maximum of a 50-mile return journey.	
6. I understand that I will undertake assessments for measurement of my muscle activity and my movement at the MoveExLab at the University of East Anglia.	
7. I understand that I will undertake questionnaires of my mood and cognition (e.g. memory). These will be undertaken at the MoveExLab at the University of East Anglia or I will self-complete them at home.	
8. I understand that I will undertake questionnaires about my sleeping pattern. These will be undertaken at the MoveExLab at the University of East Anglia or I will self-complete them at home.	
9. I understand that I will keep a sleep diary to record my sleep pattern during the time in-between my two visits to the MoveExLab at the University of East Anglia.	
10. I understand that I will wear a motion watch on each of my wrists for 7 days following each visit to the MoveExLab at the University of East Anglia and that I will then post these in the stamped addressed padded envelope given to me by the Researcher.	

11. I understand that while information gained during the study may be published, I will not be identified and all information (demographic and measures) will be anonymised.	
I agree to take part in the study. I understand that the study will involve me undertaking the activities outlined in boxes 4-10 above	

	Please initial the appropriate box	
I agree to my name and contact details being held on a secure database at the University of East Anglia so that I can be contacted regarding follow-up to this study and opportunities for future research that has been ethically approved.	YES	NO
I agree for my anonymised data captured with the Biokido system to be sent to the manufacturer in Turkey so that if can be analysed. I understand that my anonymised data will be in blurred pictorial format as in the illustration of the Biokido system in the information sheet. My data transferred to Turkey for analysis will only be identifiable by the anonymised study number.		

Name of participant	
Signature	

Date	

Name of person receiving consent	
Signature	
Date	

One original copy of this form should be completed. The original, paper or electronic, should be stored in the relevant section of the investigator site file. Photocopy of a paper form should be made of the original and given to the participant

Appendix 9 – Recruitment Advertisement for Study 3

Faculty of Medicine and Health
University of East Anglia



Brain recovery after stroke is a puzzle
Would you like to be part of the solution?

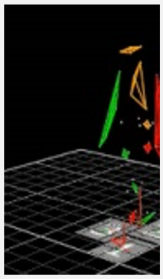
We are investigating how movement recovers after stroke and whether this is influenced by sleep.

We need people who have had a stroke to undertake measures of movement, sleep and daily activity, twice.

Measures involve answering a telephone placed on a table. First, moving from a chair to the table. Second, seated next to the table. Sleep questionnaires will also be completed. Everyday activity will be recorded by motion watches

In detail we are recruiting adults who have had a stroke and do not have a latex allergy. This project will involve measuring your movement whilst you pick up a telephone several times. To measure your movement, we will stick small reflective markers and sensors on your skin. You will complete some questionnaires about how you sleep. No painful or intrusive methods are used. You will need to attend two 90-minute sessions in the Movement and Exercise Laboratory at the University of East Anglia. And you will wear a motion watch on each wrist for 7 days to measure your everyday activity at home.






For more information please contact:
v.pomeroy@uea.ac.uk or p.fordham@uea.ac.uk

For more information: v.pomeroy@uea.ac.uk or p.fordham@uea.ac.uk
For more information: v.pomeroy@uea.ac.uk or p.fordham@uea.ac.uk
For more information: v.pomeroy@uea.ac.uk or p.fordham@uea.ac.uk
For more information: v.pomeroy@uea.ac.uk or p.fordham@uea.ac.uk
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Appendix 10 - b-DAS Assessment Battery

Brief Dimensional Apathy Scale (bDAS)

Choose the answer on how you have **felt, behaved or thought**, based on the rate of occurrence in the last month: (Circle the statement that applies)

1. I think of new things to do during the day
   - Almost always
   - Often
   - Occasionally
   - Hardly Ever
2. I am concerned about how my family feel
   - Almost always
   - Often
   - Occasionally
   - Hardly Ever
3. I am able to focus on a task until it is finished
   - Almost always
   - Often
   - Occasionally
   - Hardly Ever
4. I set goals for myself
   - Almost always
   - Often
   - Occasionally
   - Hardly Ever
5. Before I do things, I think about how others would feel about it
   - Almost always
   - Often
   - Occasionally
   - Hardly Ever
6. When doing a demanding task, I have difficulty working out what I have to do
   - Almost always
   - Often
   - Occasionally
   - Hardly Ever

7. I act on things I have thought about during the day
    - Almost always
    - Often
    - Occasionally
    - Hardly Ever
8. I am indifferent to what is going on around me
    - Almost always
    - Often
    - Occasionally
    - Hardly Ever
9. I find it difficult to keep my mind on things
    - Almost always
    - Often
    - Occasionally
    - Hardly Ever

Appendix 11 - PSQI Assessment Battery

Participant's ID.....

PITTSBURGH SLEEP QUALITY INDEX (PSQI)

The following questions relate to your usual sleep habits during the past month *only*. Your answers should indicate the most accurate reply for the *majority* of days and nights in the past month. Please answer all the questions.

1. During the past month, when have you usually gone to bed at night?

   Usual bed time: .....

2. During the past month, how long (in minutes) has it usually taken you to fall asleep each night?

   Number of minutes: .....

3. During the past month, when have you usually got up in the morning?

   Usual getting up time: .....

4. During the past month, how many hours of actual sleep did you get at night? (This may be different from the number of hours you spend in bed.)

   Hours of sleep per night: .....

For each of the remaining questions, check the one best response. Please answer all questions

5. During the past month, how often have you had trouble sleeping because you…..

a) Cannot get to sleep within 30 minutes

Not during the past month	.....	Less than once a week	.....	Once or twice a week	.....	Three or more times a week	.....

b) Wake up in the middle of the night or early morning

Not during the past month	.....	Less than once a week	.....	Once or twice a week	.....	Three or more times a week	.....

c) Have to get up to use the bathroom

Not during the past month ..... Less than once a week ..... Once or twice a week ..... Three or more times a week .....

d) Cannot breathe comfortably

Not during the past month ..... Less than once a week ..... Once or twice a week ..... Three or more times a week .....

e) Cough or snore loudly

Not during the past month ..... Less than once a week ..... Once or twice a week ..... Three or more times a week .....

f) Feel too cold

Not during the past month ..... Less than once a week ..... Once or twice a week ..... Three or more times a week .....

g) Feel too hot

Not during the past month ..... Less than once a week ..... Once or twice a week ..... Three or more times a week .....

h) Had bad dreams

Not during the past month ..... Less than once a week ..... Once or twice a week ..... Three or more times a week .....

i) Have pain

Not during the past month ..... Less than once a week ..... Once or twice a week ..... Three or more times a week .....

j) Other reason(s), please describe

.....

.....

How often during the past month have you had trouble sleeping because of this?

Not during the past month ..... Less than once a week ..... Once or twice a week ..... Three or more times a week .....

c) Have to get up to use the bathroom

Not during the past month ..... Less than once a week ..... Once or twice a week ..... Three or more times a week .....

d) Cannot breathe comfortably

Not during the past month ..... Less than once a week ..... Once or twice a week ..... Three or more times a week .....

e) Cough or snore loudly

Not during the past month ..... Less than once a week ..... Once or twice a week ..... Three or more times a week .....

f) Feel too cold

Not during the past month ..... Less than once a week ..... Once or twice a week ..... Three or more times a week .....

g) Feel too hot

Not during the past month ..... Less than once a week ..... Once or twice a week ..... Three or more times a week .....

h) Had bad dreams

Not during the past month ..... Less than once a week ..... Once or twice a week ..... Three or more times a week .....

i) Have pain

Not during the past month ..... Less than once a week ..... Once or twice a week ..... Three or more times a week .....

j) Other reason(s), please describe

.....

.....

How often during the past month have you had trouble sleeping because of this?

Not during the past month ..... Less than once a week ..... Once or twice a week ..... Three or more times a week .....

c) Legs twitching or jerking while you sleep

Not during the past month	.....	Less than once a week	.....	Once or twice a week	.....	Three or more times a week	.....

d) Episodes of disorientation or confusion during sleep?

Not during the past month	.....	Less than once a week	.....	Once or twice a week	.....	Three or more times a week	.....

e) Other restlessness while you sleep; please describe

.....

.....

Not during the past month	.....	Less than once a week	.....	Once or twice a week	.....	Three or more times a week	.....

Appendix 12 - GAD-7 Assessment Battery

Participant's ID. ..... Date:.....

Generalized Anxiety Disorder-7 (GAD-7)

Instruction

Over the last 2 weeks, how often have you been bothered by any of the following problems?

	Not at all	Several days	More than half the days	Nearly every day
1. Feeling nervous, anxious, or on edge	0	1	2	3
2. Not being able to stop or control worrying	0	1	2	3
3. Worrying too much about different things	0	1	2	3
4. Trouble relaxing	0	1	2	3
5. Being so restless that it's hard to sit still	0	1	2	3
6. Becoming easily annoyed or irritable	0	1	2	3
7. Feeling afraid as if something awful might happen	0	1	2	3

Appendix 13 - PHQ-9 Assessment Battery

Participant's ID.....

Patient Health Questionnaire-9 (PHQ-9)

Instruction

Over the last 2 weeks, how often have you been bothered by any of the following problems?

	Not at all	Several days	More than half the days	Nearly every day
1. Little interest or pleasure in doing things	0	1	2	3
2. Feeling down, depressed, or hopeless	0	1	2	3
3. Trouble falling or staying asleep, or sleeping too much	0	1	2	3
4. Feeling tired or having little energy	0	1	2	3
5. Poor appetite or overeating	0	1	2	3
6. Feeling bad about yourself — or that you are a failure or have let yourself or your family down	0	1	2	3
7. Trouble concentrating on things, such as reading the newspaper or watching television	0	1	2	3
8. Moving or speaking so slowly that other people could have noticed? Or the opposite — being so fidgety or restless that you have been moving around a lot more than usual	0	1	2	3
9. Thoughts that you would be better off dead or of hurting yourself in some way	0	1	2	3

Appendix 14 - Sleep Diary

Date:..... Time:.....

The following sleep questions should be completed in the morning after you have woken up. Please fill in the date and time above. You should try to complete these questions at the time rather than providing answers retrospectively if possible. *Please indicate whether the time is AM or PM.*

What time did you go to bed?		**AM/PM**
What time did you try starting to sleep at?		**AM/PM**
How long did it take you to fall asleep? (min)		
How many times did you wake up?		
How long were you awake for? (min) Please estimate the time and duration of each night awakening		
What time did you wake up?		**AM/PM**
What time did you get up?		**AM/PM**
Did your alarm clock wake you up?		
Did you do any strenuous activity during the last 24 hours (if yes, please specify)		

How would you rate your quality of sleep?

1 2 3 4 5 6 7 8 9

Best sleep ever. Worst sleep ever

Appendix 15- FMA -LE Assessment Battery

FMA-LE PROTOCOL — Rehabilitation Medicine, University of Gothenburg

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

ID:
Date:
Examiner:

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

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

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

H. SENSATION, lower extremity eyes closed, compare with the unaffected side		**anesthesia**	**hypoesthesia or dysesthesia**	**normal**
Light touch	leg foot sole	0 0	1 1	2 2
		less than 3/4 correct or absence	**3/4 correct or considerable difference**	**correct 100%, little or no difference**
Position small alterations in the position	hip knee ankle great toe (IP-joint)	0 0 0 0	1 1 1 1	2 2 2 2
	Total H (max12)			

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

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

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

Appendix 16 – Instructions for Actigraphy Watches

GENEActiv Instructions

1. **Wear the GENEActiv marked with a red colour "R" sign to your right wrist.**



2. **Wear the GENEActiv marked with a blue colour "L" sign to your left wrist.**



3. **Wear GENEActivs for at least one consecutive 48-hour period and ideally a period of seven consecutive days, even when you are sleeping.**



IDEALLY 24/7 HOURS



EVEN SLEEPING



4. **The GENEActiv is waterproof. However, we advise to take GENEActivs off when they are likely to get wet e.g. personal washing activity. Please do not forget to put it back afterwards.**



5. **On each of the seven days, a researcher will telephone you to check whether there are any challenges and/or discomforts in using GENEActivs to help you to solve these. You can also contact directly the researcher if you need any help regarding these devices without waiting for a call from the researcher, as well.**



6. **At the end of the seven-day period, please send these GENEActivs to us using the stamped addressed padded envelope, provided**



to you with these devices.

NOTES:

- **Please ensure that GENEActivs are kept out of reach of children as it contains a coin cell battery that can pose a potential swallowing hazard if the casing were to be opened.**
- **If the device becomes warm to the touch whilst in use, remove it and inform the researcher in daily phone calls about this issue.**
- **If there needs, clean the device with a soft moistened cloth. Do not use abrasive cleaners or solvents.**
- **Do not subject the device to excessive force, shock or extreme temperature changes.**
- **Do not use an external heat source such as a hairdryer or heater to dry the device.**

Appendix 17 – Written instructions regarding home assessment

Karolinska Sleep Diary (KSD) and actigraphy

Dear ……..

You have received this pack and actiwatch because you have volunteered to take part in the study: 'Relationship between motor function, functional ability and sleep after stroke, and, criterion validity of measures made by the Vicon and Biokido motion analysis systems

In the following text we will remind you of the instructions we gave you in the MoveExLab for how to use the sleep and activity diary and also the actiwatch

1. Sleep and activity diary

Within this pack you will find a set of pages each of which is the questionnaire for you to repeat every day for one week. You should complete **both** the morning and the evening sections of the diary every day for the duration of one week (7 days). It is important that you try to complete the diary at the time intended for completion rather than completing the answers retrospectively, so your answers are as accurate as possible. However, if you forget to fill in the diary please leave it blank rather than trying to complete it from memory several days later when you are not sure about the details.

2. The actiwatch

We have provided you with an instruction leaflet in this letter/email. In addition, here are some written instructions

1. Wearing the watches

You should wear the actiwatches continuously on your wrists during the 7 days (one week). You can take them off occasionally for a short time. Please do not forget to put them back afterwards. The actiwatches are waterproof.

The actiwatches should be fastened as you would a normal wristwatch. You can adjust the strap to ensure this is comfortable on your wrist.

2.2 Precautions

Actiwatches are not designed to be worn on irritated or damaged skin. In the unlikely event that you experience any discomfort or irritation please try to keep wearing the actiwatch on you other wrist. Ideally the actiwatch should stay on your non-dominate wrist. If you need to remove an actiwatch because of irritation then please make a note in your sleep diary. If you continue to experience discomfort please notify the research team.

As with similar devices you should also ensure that the actiwatch is kept out of reach of children. I It contains a coin cell battery that can pose a potential swallowing hazard if the casing were to be opened.

You are not required to open the actiwatch while it is in your possession.

At the end of the 7-day period

Once you have completed all of the forms enclosed within this pack these can then be sent back to the study team. The actiwatches should be put in the same stamped addressed padded envelope that we gave you in the MoveExLab.

Contact us if you have any questions or concerns. We will be pleased to answer any questions.

Thank you again for taking part in this study.

Researcher email:

Researcher telephone number:

Appendix 18 - Actigraphy Samples from this project

Please note that Date of Birth and Gender section is automatically generated does not connect the real data. Green and Blue sections together represent rest period, but Blue represent sleep period. However, red lines under the graph represent activity epochs which means if they are in sleep period they considered as wakefulness after sleep (WASO).

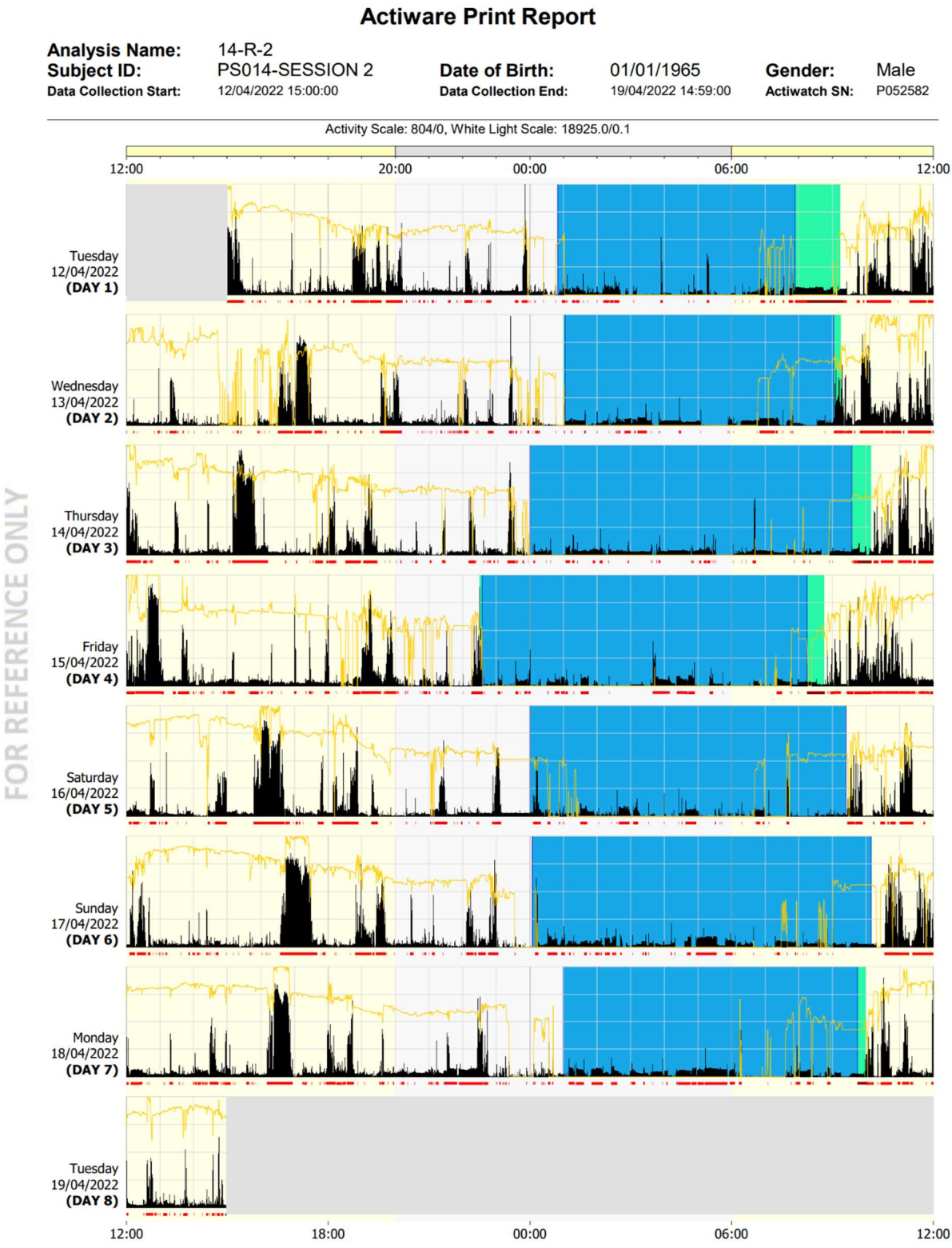


Figure 0-1 Actigraphy Sample 1 created by Philips Actiware 6.0.4 Software

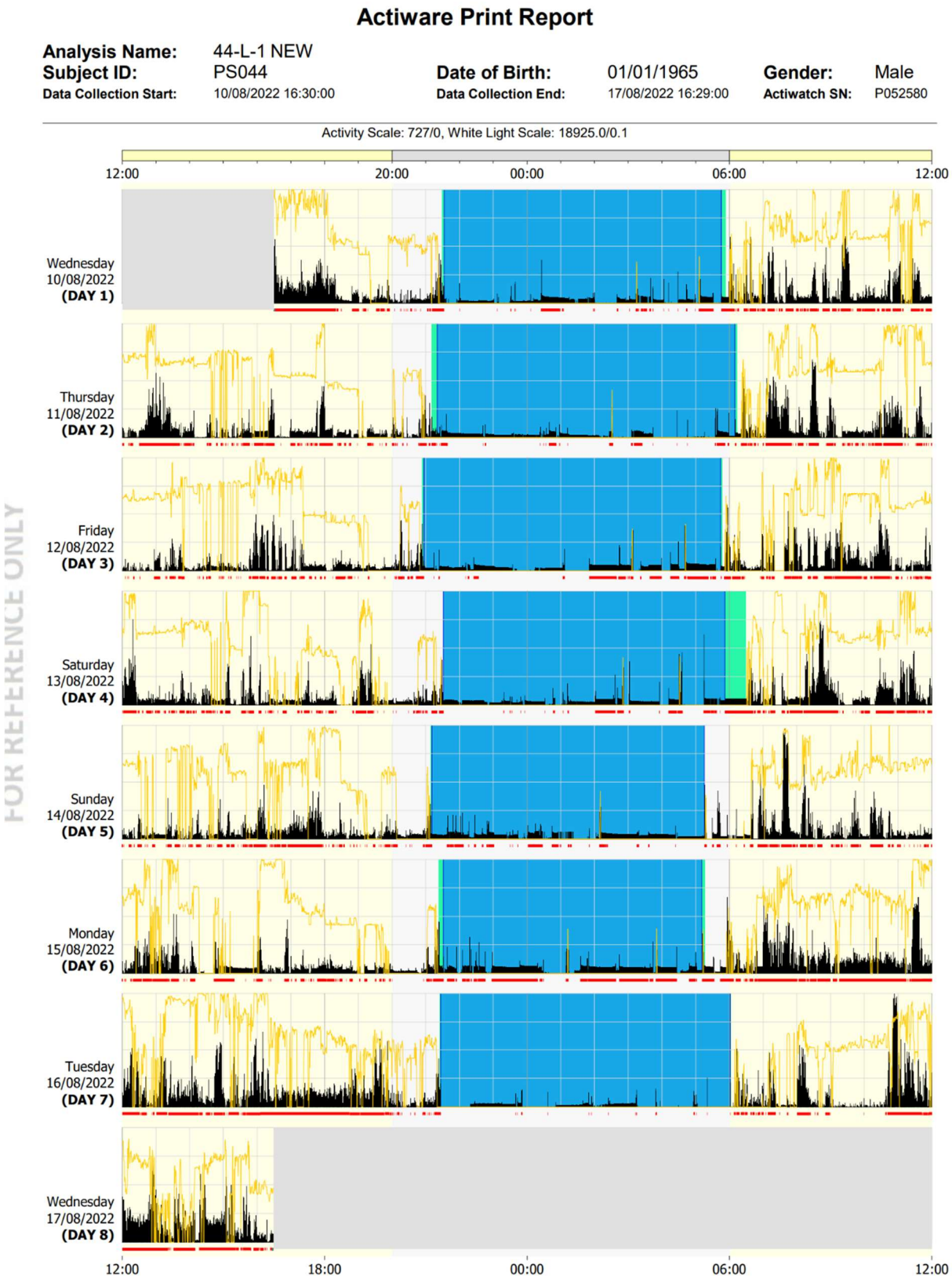


Figure 0-2 Actigraphy Sample 2, created by Philips Actiware 6.0.4 Software

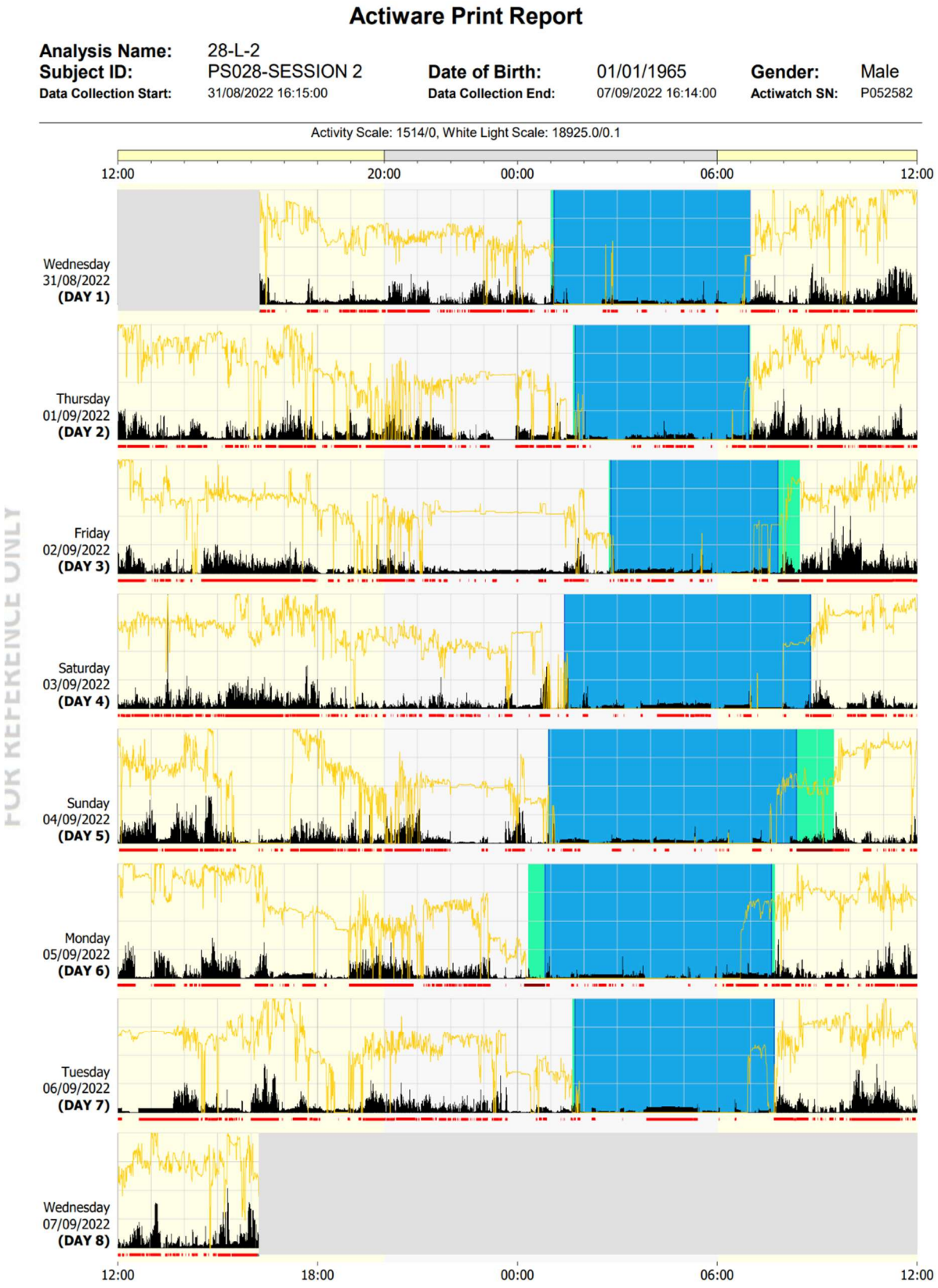


Figure 0-3 Actigraphy Sample 3, created by Philips Actiware 6.0.4 Software

Appendix 19 – Summary of PSQI Qualitative Questions

The qualitative section of the Pittsburgh Sleep Quality Index (PSQI), which captures self-reported sleep disturbances beyond numerical scores, highlighted more severe sleep difficulties than the sleep diary alone suggested. An analysis of sleep disturbance data from 44 stroke patients—15 with one recorded session and 30 with two. Using a threshold where a score of "3" (indicating occurrence three or more times per week) on any session of the Pittsburgh Sleep Quality Index (PSQI) was considered, the results showed frequent and varied sleep disruptions. Difficulties maintaining sleep were commonly reported, with 35 participants indicating this issue in at least one of their two assessment sessions. Similarly, 33 participants reported nocturnal awakenings to use the bathroom in at least one session. Pain-related sleep disturbance was reported by five participants, with descriptions including joint or limb discomfort, neck pain, and issues related to uncomfortable positioning. A further nine participants identified other causes of disrupted sleep, including nocturnal restlessness, rigidity in the upper or lower limbs that impaired mobility, and difficulty adjusting posture. Environmental factors—such as external noise, changes in the sleeping environment (the presence of a new pet), and thermal discomfort—were also reported. Lifestyle factors, such as irregular sleep-wake routines and staying up late, is noted in one case. Medical issues, including the use of diuretics, prostate-related symptoms (1) were included the notes. Furthermore, one case of sleep apnoea and one case of insomnia existed in the group.