Sonic Sleeve: Reducing Compensatory Movements of the Upper Limb in Participants with Chronic Stroke Using Real-time Auditory Feedback

Pedro Douglass-Kirk

Department of Psychology
Goldsmiths, University of London

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Declaration

Declaration of Authorship

I, Pedro Douglass-Kirk hereby declare that this thesis, and the work presented in it, is my own. Where I have consulted the work of others, this is always clearly stated.

Signed: Date: March 15th 2024

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Related Publications and Presentations

The research reported in Chapter 5 is published in:

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The research reported in Chapter 5 and 6 have been presented at various conferences:

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Douglass-Kirk, P. (2021, March) Invited career talk to 2nd-year undergraduate music students at University of Cambridge, taking the course 'Introduction to Music & Science", live on Zoom.

Douglass-Kirk, P. (2018, Oct). Invited Speaker: *Music the Brain and Recovery*. PowerPoint presentation: Celebrating Optimism and Hope Post Stroke: Music and Neural Plasticity. Sonic Arts Research Centre, Queen's University, Belfast.

Douglass-Kirk, P. (2018, June). Invited Speaker: *Music the Brain and Recovery*. PowerPoint presentation: 6th Annual Queen Square Upper Limb Neurorehabilitation Course: Treating Patients With Upper Limb Deficit: Integrating Research Into Practice. Queen Square, London.

List of Figures

List of Tables

List of Abbreviations

ADL	Activities of daily living
AI	Artificial Intelligence
API	Application Programming Interface
CAHAI	Chedoke Arm and Hand Activity Inventory
CIMT	Constraint Induced Movement Therapy
CNN	Convolutional neural networks
DV	Dependent Variable
FMA	Fugl-Meyer Assessment
HCI	Human Computer Interaction
IML	Interactive Machine Learning
IMU	Inertial Measurement Units
KNN	K-Nearest Neighbors
KP	Knowledge of performance
KR	Knowledge of results
ML	Machine Learning
MST	Music supported therapy
NN	Neural network
NMT	Neurologic Music Therapy
OT	Occupational therapist
PIS	Participant Information Sheet
PT	Physiotherapist
QSUL	Queen Square Upper Limb
RAC	Rhythmic auditory cueing
RAS	Rhythmic auditory stimulation
RCT	Randomised Controlled Trial
RGB	Red, Green, Blue
SART	Sustained Attention to Response Task
SUS	System Usability Scale
TAM	Technology Acceptance Model
TIDieR	Template for Intervention Description and Replication
REC	Research Ethics Committee
RCT	Randomised control trial
VR	Virtual reality
WMFT	Wolf Motor Function Test

Abstract

Chronic stroke patients with upper limb impairments are encouraged to undertake many repetitions of movements to aid their rehabilitation. Providing personalised feedback on their repetitions and movement quality could be beneficial. One approach to provide feedback for patients is to map movements directly onto sound. This thesis investigates the use of auditory feedback, particularly to provide patients with real-time knowledge of their movement quality, much as a clinician uses verbal and physical support during therapy sessions. The methodological frameworks underpinning this proof-of-concept work include co-creation, participatory design, and interactive machine learning. Participatory design workshops facilitated collaboration among experts in stroke rehabilitation, music psychology, motor neuroscience, and human-computer interaction, resulting in the development *Sonic Sleeve*, a bespoke stroke rehabilitation system. Iterative case studies parallel to the workshops with service users refined the system. A significant reduction of compensatory movement was observed in the first lab-based experiment that recruited 20 participants with chronic stroke, *F*(1,18) = 9.424, *p*=.007, with a large effect size (partial =.344). There was evidence for successful replication with 4 participants with chronic stroke in the home environment. A second set of experiments investigated whether an extended training period with auditory feedback may elicit learning without auditory feedback. However, there was no statistically significant interaction between group and time on the duration of compensatory movement as a proportion of total movement time, *F*(1.346, 9.422) = 0.453, *p* = .574, partial η2 = .061. This thesis addresses the limited research on using auditory feedback, specifically patient-selected music, combined with interactive machine learning to reduce compensatory movement and enhance reaching quality in chronic stroke rehabilitation. It makes three key contributions by demonstrating reductions in compensatory movements beyond trunk flexion, integrating patient-selected music to motivate high dose, and introducing an interactive machine learning approach for personalised treatments.

Table of Contents

CHAPTER 1: SHORT INTRODUCTION, GENERAL AIMS AND THESIS OUTLINE

1.1 Introduction

Every year, an estimated 15 million stroke cases are reported globally, resulting in significant disabilities for around 5 million survivors (WHO, 2021). Alongside the human toll, strokes impose substantial strains on healthcare systems, with considerable financial costs. In the United Kingdom, stroke-related expenses amount to an estimated £26 billion annually (King et al., 2020). Moreover, stroke survivors often lack adequate formal support, leading to an increased risk of secondary strokes (Joice, 2012). Additionally, hemiplegia, paralysis affecting one side of the body, commonly follows strokes, further complicating rehabilitation efforts (Chohan et al., 2019). The upper limb tends to be overlooked despite its crucial role in daily activities such as cooking, cleaning, and personal care (Lang et al., 2009).

Addressing these complex challenges requires innovative approaches to facilitate the recovery and rehabilitation of stroke survivors. Establishing frameworks that motivate survivors to engage in physically demanding exercises at home is crucial. To attain the optimal exercise "dose" for effective motor plasticity — supported by animal studies suggesting 400 to 600 repetitions a day (Kleim et al., 1998; Plautz et al., 2000) — such frameworks must inherently provide intrinsic rewards. This concept aligns with gamification principles in human-computer interaction (HCI) research, where patient motivation and engagement significantly enhance treatment outcomes (Tuah et al., 2021).

1.2 Auditory Feedback and Music Integration in Stroke Rehabilitation

The integration of auditory feedback, particularly through music, emerges as a promising avenue for effective rehabilitation (Schaffert et al., 2019). Auditory cues, especially those provided by music, offer advantages over visual cues in facilitating motor responses driven by the intricate connections between cortical auditory and motor systems (Hove et al., 2010). The auditory-motor interaction is of interest; listening to musical rhythms triggers activation in cerebral motor regions (Chen et al., 2008), signifying that music has the capacity to stimulate motor functions. This convergence underscores the potential of auditory feedback, particularly through music, as a promising tool for stroke rehabilitation.

Moreover, the potential application of music extends to active music-making in stroke rehabilitation, presenting an intriguing avenue for exploration. This notion gains support from research in the realm of sports science, which highlights that exercising to music can lead to a reduction in perceived effort for the same level of exertion — an effect attributed to the motivational impact of music (Karageorghis, 2013; Priest & Karageorghis, 2008). This intrinsic connection between music and physical effort highlights the potential benefits of integrating music into stroke rehabilitation. Consequently, the core objective of the present thesis is to harness the intrinsic qualities of music to specifically aid in the rehabilitation of the upper limb, tapping into its motivational properties to drive recovery.

Before embarking on this current research, the author and colleagues reported results that established the role of self-selected favourite music as a motivational tool for physical therapy. Notably, patients engaged in hundreds of repetitions of their target movements in response to the motivational context created by self-selected music (Kirk et al., 2016). These findings provide a firm foundation to further integrate real-time auditory feedback into stroke rehabilitation. This integration aims to provide patients with crucial, immediate insight into the quality of their movements with the optimal patterns identified by highly trained occupational and physical therapists working directly with a bespoke system built using computer vision and machine learning technologies.

1.3 Research Gaps

While prior research has established the motivational impact of music in rehabilitation contexts (Schaffert et al., 2019), there remains a gap between this recognition and the practical application of self-selected music in physical rehabilitation settings. Additionally, limited research employs real-time auditory feedback as a means to reduce compensatory strategies beyond trunk flexion in upper limb rehabilitation (Pain et al., 2015; Valdés & Van der Loos, 2018). Most prior work focuses on trunk flexion alone rather than providing feedback on multiple forms of compensation, such as shoulder abduction and elevation. The research seeks to address gaps around utilising auditory feedback and patient-centred music selection for compensatory movement reduction and improved reaching quality in chronic stroke. A key element of novelty is the application of interactive machine learning, allowing clinician guidance of algorithms toward customised auditory feedback matched to an individual's abilities and progress. This approach combines human expertise with data-driven learning for more adaptive and personalised treatments.

1.4 General Thesis Aims and Research Questions

The overarching aims of this proof-of-concept research are to investigate the integration of real-time auditory feedback, specifically through the application of music, for enhancing motor re-learning among stroke survivors with upper limb impairment. The research seeks to explore the potential of novel sound technologies using interactive machine learning to aid upper limb rehabilitation, utilise sound-based feedback to promote movement quality and examine participant preferences for sound feedback. Moreover, the research intends to investigate whether participants can perceive and effectively utilise auditory feedback to reduce compensatory movements during specific tasks. Additionally, the research hypothesizes that active forward-reaching movements, coupled with self-selected favourite music and auditory feedback, can lead to a reduction in compensatory movements. Furthermore, the research investigates whether participants can retain their improved movement patterns even after the withdrawal of auditory feedback. The key research questions addressed in the thesis are as follows, with the respective chapters noted:

(1) What are the key clinical considerations for upper limb rehabilitation? [Chapter 3]

(2) What potential is there for novel technologies using sound to aid upper limb rehabilitation? [Chapter 3]

(3) How can sound be used to promote movement quality in upper limb rehabilitation? [Chapter 3]

(4) What sound feedback is preferred by participants with chronic stroke? [Chapter 4]

(5) Can participants with chronic stroke notice changes to sound based on their movements? [Chapter 4]

(6) What are the optimal number of movements and rest periods when using auditory feedback? [Chapter 4]

(7) Can participants with chronic stroke perceive and make use of auditory feedback (muting within self-selected music) to reduce compensatory movements in a seated active forward-reaching task? [Chapter 5]

(8) Are there differences in clinical baseline characteristics between participants who show larger versus smaller reductions in compensatory movements with auditory feedback? [Chapter 5]

(9) Can participants with chronic stroke who engage in a training session with auditory feedback for 200 repetitions learn to reduce compensation even when this feedback is no longer present immediately after training (short-term retention) and 24 hours later (longer-term retention)? [Chapter 6]

(10) Can participants with chronic stroke who engage in a training session with auditory feedback for 200 repetitions in the home learn to reduce compensation even when this feedback is no longer present immediately after training (short-term retention) tracked over a longer period of 10 days? [Chapter 6]

1.5 Thesis Outline

The literature review in Chapter 2 covers a range of relevant research areas that form the foundation for the proof-of-concept research described in this thesis. The review does not aim to be exhaustive but to place stroke rehabilitation of the upper limb into context, highlighting some of the standard practices and controversies before introducing relevant literature where music and real-time auditory feedback strategies are used in rehabilitation contexts. Furthermore, the use of robotics and other technologies using machine learning are summarised alongside the use of co-creation as a methodology for designing new systems where users are critical to the verification and validation of the system.

Formative research development is described and involves an iterative research co-creation process including workshops with health experts (Chapter 3) and multiple user-centred sessions with participants with chronic stroke and staff on the Queen Square Upper Limb (QSUL) neurorehabilitation programme (documented in Chapter 4). The workshops with health experts started in the fall of 2017 with the user sessions running in parallel relatively quickly, meaning that the end users of the system were involved from an early stage of development. Chapter 4 highlights the importance of user acceptability and usability in system design. User feedback from participants with chronic stroke was crucial for evaluating and refining the real-time auditory feedback system. The case studies involved participant preferences for music types and auditory feedback. The primary aim was to gather direct user feedback, while the secondary aims focused on technical development and the creation of a robust research protocol.

The first set of experiments is described in Chapter 5 and aimed to establish if patients could make use of auditory feedback to reduce compensation of three distinct types: i) trunk flexion ii), shoulder abduction, or iii) shoulder elevation. The selection of these three movement types came directly from feasibility research where health experts were interested in more strategies tracked than trunk flexion alone. Furthermore, these three compensatory types have been studied in many clinical trials and summarised in a recent systematic review that reported 46 studies using technology to monitor compensation on trunk flexion, 17 studies on shoulder elevation, and five on shoulder abduction (Wang et al., 2022). The most common tasks reported were forward-reaching tasks. The current thesis also reports on implications for home-based stroke rehabilitation based on direct feedback from stroke patients using the bespoke system created for the research. A second set of experiments described in Chapter 6 investigated whether training with this feedback could promote learning such that reduced compensation would also be seen in the absence of auditory feedback. Support for the second experiment came from the assertion that if there is skill learning with no retention, this is of little use to a patient's rehabilitation trajectory (Krakauer & Carmichael, 2017). The final Chapter 7 reviews and summarises the findings and limitations alongside recommendations for future research in auditory feedback and stroke rehabilitation.

CHAPTER 2: LITERATURE REVIEW

This literature review provides an overview of key research relevant to using auditory feedback for upper limb rehabilitation for patients with chronic stroke. The review begins by summarising the current state of upper limb stroke rehabilitation, including controversies around functional versus impairment-focused approaches (Section 2.1). High dose, high quality practice and the role of motor learning principles are discussed. Reducing compensatory movements and the importance of motivation are also covered. Section 2.2 overviews major technology-enabled methods transforming stroke rehabilitation, such as robotics, virtual reality, computer vision, wearables, telerehabilitation, and artificial intelligence. Section 2.3 introduces co-creation and user-centred design approaches, including participatory design, rapid prototyping, and human-computer interaction techniques. The potential of music-based interventions for stroke rehabilitation is covered in Section 2.4, including passive music listening, patient-selected music, music-supported therapy, and possible underlying mechanisms. Section 2.5 focuses specifically on auditory feedback techniques rhythmic auditory cueing, real-time sonification mapping and the use of auditory feedback to reduce compensatory movements. Finally, Section 2.6 concludes by summarising key gaps and opportunities highlighted in this review at the intersection of auditory feedback, interactive machine learning, and upper limb stroke rehabilitation. Overall, this review covers core background literature motivating the thesis research on compensatory movement reduction through real-time auditory feedback that is supported by interactive machine learning.

2.1 Upper Limb Rehabilitation in Stroke: Where is the Field?

2.1.1 Current Treatment

There are two key approaches to rehabilitation. One focuses on improving function or activity while the other focuses on recovery of impairment. The former has been the more common treatment approach in stroke rehabilitation since the 1980s and involves training on functional, real-life tasks (Krakauer & Carmichael, 2017). There is a focus on reducing disability by helping stroke patients achieve as much independence as possible in activities of daily living (ADL). This focus on ADL can help achieve the tasks and reduce dependence on caregivers and health experts. However, compensatory movements and strategies are often used that may incur long-term issues such as reduced joint motion and pain (Levin et al., 2009). An example of a pure compensation strategy is where a patient uses their unaffected arm to complete a task; a clear compensatory strategy that may well help them achieve a task but will not rehabilitate the affected limb. This functional or activity approach has been the core ethos of most stroke rehabilitation with few exceptions (Dobkin, 2004) and task accomplishment is the primary goal, with little attention to the quality of the task performance (Levin et al., 2009).

In contrast to “functional compensation” (Kitago & Krakauer, 2013), the second approach to neurorehabilitation is to target impairment directly. Impairment of the upper limb is a loss of strength and motor control (Raghavan, 2015). To recover from impairment, a patient needs to achieve the same movement patterns used prior to their stroke (Kitago & Krakauer, 2013). Reduction of impairment is often assessed by the Fugl-Meyer Motor Assessment (Fugl-Meyer et al., 1975) and more recently can be assessed with the use of kinematic analysis to observe changes in movement (Krakauer et al., 2012). Recovery of impairment can be achieved by reducing or removing the ability of a patient to use compensatory strategies. Stroke patients have shown to be able to reduce their impairment levels by reducing compensatory strategies such as trunk flexion (Michaelsen et al., 2001; Woodbury et al., 2009). By reducing the compensation patients can move towards more “normal” movement patterns that are reminiscent of a patient’s pre stroke condition (Kitago & Krakauer, 2013).

There needs to be more clarity about these two approaches in the literature (functional compensation versus recovery of impairment), and it is essential to differentiate between them to understand how learning is affected (Kitago & Krakauer, 2013). Clinical outcome measures such as the Action Research Arm Test (Yozbatiran et al., 2008) or other assessments of ADL are used to assess functional outcomes, but these measures cannot discriminate between recovery of impairment and compensatory strategies (Schwarz et al., 2019). Krakauer et al. (2012) make a strong case that research needs to focus on reducing impairment levels not on function because impairment reflects true biological repair mechanisms. To reiterate the key issue is that any functional gains that a chronic stroke patient may have could be down to compensatory strategies rather than true recovery or restitution (Levin et al., 2009). True recovery is recovery at the neuronal level with a return to more normal behaviours used pre injury while compensation substitutes new strategies to achieve a task rather than using the normal pre-stroke behaviours (Bernhardt et al., 2017). It is argued that restitution is minimal in the chronic phase of recovery (Krakauer & Carmichael, 2017). Therefore, improvements reported in chronic stroke patients may be based on levels of compensation rather than impairment reduction (Krakauer, 2006). However, there is evidence from three recent studies (Daly et al., 2019; McCabe et al., 2015; Ward et al., 2019) that with a high dose of rehabilitation exercises chronic stroke patients (six months or more post stroke) can achieve clinically significant reductions in impairment of the upper limb.

2.1.2 The Benefit of High Dose

Neuroplasticity describes the ability for the brain to change and adapt and has been investigated in animal models where many hundreds of repetitions of target movements are required to induce cortical changes in both healthy animals and those with induced lesions (Krakauer et al., 2012). Models in healthy squirrel monkeys suggest 400-600 repetitions of upper limb tasks are required to alter cortical plasticity (Kleim et al., 1998; Nudo et al., 1996). A stroke model with squirrel monkeys reported between 500 and 600 repetitions per day for up to two weeks; the monkeys had to retrieve pellets with many repetitions required to gain full recovery of the primary motor cortex (Friel et al., 2007). Large numbers of repetitions are also required in healthy human participants who engage in hundreds of repetitions of specific targeted upper limb movements to induce learning (Kleim & Jones, 2008). This leads to the question: in stroke rehabilitation what is the dose required?

Rehabilitation dose of the upper limb in humans have been argued to be far too low to lead to meaningful improvement in the acute phase (Krakauer & Carmichael, 2017). This assertion is based on research from Bernhardt and colleagues (Bernhardt et al., 2004) who documented acute patients over two days from 8 am to 5 pm during their first few weeks in hospital. They found that patients were alone for up to 60% of the day with 50% spent in bed and only active 13% of the time. It is important to note that these patients were not yet in an acute rehabilitation ward, but Krakauer & Carmichael (2017) argue that due to heightened plasticity the first few weeks post-stroke may be of critical importance for reducing impairment over and above any spontaneous recovery (i.e. recovery not linked to any rehabilitation but rather the reorganisation of neural connections post-stroke). Another study from Lang and colleagues (2009) observed that patients in an acute ward only received 30 minutes of upper limb rehabilitation per day. Furthermore, patients only achieved on average of thirty-two functional repetitions. The repetitions were spread between two and four functional tasks, so the final number of repetitions was undoubtedly far lower than those found in animal models. Another explanation for the upper limb being neglected in rehabilitation is that there is a far greater emphasis on gait training and mobility to minimise expensive stays in hospital (Levin et al., 2009).

One well-established rehabilitation programme that uses a far higher dose than standard care is that of constraint-induced movement therapy (CIMT). The stronger arm is constrained to prevent use, so the weaker arm must be used during training. CIMT is suggested to reduce “learned non-use” of the affected arm and with the use of shaping (incremental steps relevant to functional behaviour) patients can improve in function (Taub & Uswatte, 2005). Clinical improvements after CIMT have been shown in the functional Action Research Arm Test but not in tests of impairment such as the upper extremity Fugl-Meyer and kinematic measures. These outcomes imply that patients improve by using compensatory strategies (Kitago et al., 2013). It has been suggested that chronic stroke patients may not be able to achieve a high enough dose to see large improvements in functional outcomes (Lang et al., 2016). The study undertaken by Lang and colleagues (2016) showed that patients can achieve around 300 task-based repetitions per hour which is far closer to what animal models suggest is required for reducing impairment. Unfortunately, outcome measures did not include tests of impairment. However, the randomised control trial (RCT) by McCabe and colleagues (2015) reported clinical changes in 48 chronic patients after 300 hours of upper limb therapy over 12 weeks. The dose in the study is of a magnitude higher than that seen in other studies and may explain the negative results from Lang and colleagues (2016) and the generally small, reported effects in other studies as summarised in a Cochrane review (Pollock et al., 2014). The McCabe study used a motor-learning based treatment, and this was likely a crucial component (Krakauer & Carmichael, 2017). Patients in the study had severe paresis, therefore exercises were very targeted starting with exercises to move individual joints before working up hierarchically to functional task-based exercises. The authors described the movement practice as being as “close to normal as possible” with a focus on quality of movement (McCabe et al., 2015). There was a large reduction in impairment as evidenced by Fugl-Meyer scores changing by a clinically meaningful amount 8-11 points; the minimum meaningful effect size for the upper extremity Fugl-Meyer is a change of 7 points (Gladstone et al., 2002).

The success of the McCabe 2015 study has been corroborated by a follow-up study (Daly et al., 2019) in severely impaired stroke patients greater than 1 year post stroke, where large clinically significant gains were achieved. Furthermore, publications from Ward and colleagues (Kelly et al., 2020; Ward et al., 2019) from the high-intensity Queen Square Upper Limb (QSUL) neurorehabilitation programme in London, UK provide further evidence that high dose may be beneficial to chronic stroke patients. However, it is important to consider the level of evidence that high dose is beneficial for chronic stroke rehabilitation and the studies referred to fall into different levels within the evidence pyramid (Murad et al., 2016). Positioned within the hierarchy of the pyramid, these studies offer support for the effectiveness of high dose interventions. Nonetheless, it is worth noting that the Cochrane review from Pollock and colleagues (2014) reported limited evidence for significant effects, placing these findings within the broader context of research reliability. Furthermore, the single-site and lack of controls for the Ward et al. (2019) study positions it at a lower level within the evidence pyramid, necessitating careful consideration.

Despite this limitation, Ward and colleagues report on a considerably larger sample size than the RCTs mentioned above, with 224 chronic stroke patients undergoing three weeks (90 hours) of intensive rehabilitation and subsequent six-week and six-month follow-ups. The programme emphasises reducing impairment, re-educating patients on using their affected limb in activities of daily living, individualised goal setting, and focusing on movement quality (Ward et al., 2019). Clinically significant improvements were found after administering the upper limb Fugl-Meyer, with a 9-point increase at six-month follow-up. Standard functional assessments also indicated significant improvement. Ward and colleagues (2019) suggest that many studies despite high repetitions of target movements such as Lang et al. (2016) may still lack sufficient dose in terms of active training hours.

The studies by Daly, McCabe and colleagues (2015; 2019) provide compelling evidence that time on task is likely crucial, although targeted clinical studies are needed for replication and to explain the significant reduction in the Fugl-Meyer impairment scale. Krakauer & Carmichael (2017) suggest two possibilities: either the 300 hours of massed practice reduced impairment or the training led to strength gains only. Additional support comes from a recent Cochrane review (Clark et al., 2021) where a comparison between studies with greater or lesser time undertaking rehabilitation resulted in a significantly greater improvement in activity measures of the upper limb and ADL. The authors suggest a minimum difference of 16 hours and 40 minutes (1000 minutes) of total rehabilitation time to elicit a small but significant improvement in ADL outcomes. However, the authors state that the quality of evidence could be higher and to gain a true understanding of dose, better designed RCTs are required.

In summary, evidence suggests that dose is likely significant in both acute and chronic stroke rehabilitation, potentially even involving a threshold where the upper limb may either improve or deteriorate based on dose (Han et al., 2008).

2.1.3 Motor Control and Motor Learning Principles in Stroke Rehabilitation

Motor control and motor learning are fundamental concepts in the field of rehabilitation, playing a pivotal role in the recovery of individuals who have experienced a stroke, particularly concerning upper limb function. This section provides an overview of motor control and motor learning principles and explores some key theories that guide upper limb stroke rehabilitation.

Motor Control vs. Motor Learning

Motor control refers to the process by which the nervous system plans, coordinates, and executes movements focusing on the immediate, real-time control of motor actions (Schmidt & Lee, 2019). Motor control in upper limb rehabilitation involves the immediate, real-time execution of movements during therapy sessions. In contrast, motor learning refers to the relatively permanent changes in motor skills or behaviours that occur because of practice and experience. In stroke motor learning refers to the re-learning of movement patterns lost post-stroke (Hatem et al., 2016) and there is general agreement that intensive practice is vital to promote learning (Winstein & Stewart, 2006). Both motor control and motor learning are essential in the rehabilitation of upper limb motor function post stroke.

Theoretical Frameworks

Two theories provide a framework to understand motor control and motor learning in stroke rehabilitation. Schema Theory, proposed by Schmidt (1975) offers insights into motor control and learning, particularly in stroke rehabilitation. It emphasizes the role of pre-structured motor programs known as Generalized Motor Programs (GMPs). These programs are developed and refined through practice, with feedback playing a crucial role in error detection and correction, allowing individuals to adjust their movements in real-time. Dynamic Systems Theory, introduced by Newell (1986), takes a broader perspective on motor control and learning. It recognizes the dynamic interactions between individuals, tasks, and environments, which lead to self-organized coordination. While it emphasizes open-loop feedforward control mechanisms developed through practice, it also acknowledges the ongoing role of feedback processes in fine-tuning movements.

Implicit and Explicit Motor Learning

Two forms of motor learning are implicit and explicit learning. Implicit motor learning happens unconsciously through repetitive practice where a skill is acquired without awareness of the learned knowledge (Schmidt & Lee, 2019). In contrast, explicit learning involves consciously accessing knowledge to actively develop a skill relying on working memory and executive functions (Kleynen et al., 2020). After stroke, implicit re-learning of lost motor skills through extensive repetition is promoted, reducing dependence on diminished executive resources. Explicit strategies are initially required to retrain skills, but implicit learning should take over with enough practice (Kleynen et al., 2020). Finding the right balance between implicit and explicit modes is key for optimising motor re-learning in neurorehabilitation. Augmented feedback, like knowledge of performance coaching, helps transition towards implicit learning over time (Maier et al., 2019).

Optimal Challenge in Rehabilitation

To promote skill acquisition in stroke rehabilitation, the Challenge Point Hypothesis, proposed by Guadagnoll & Lee (2004) and expanded upon by Brown et al. (2016) suggests that optimal learning occurs when tasks are appropriately challenging — neither too easy nor too difficult. In upper limb stroke rehabilitation, this theory implies that therapy activities should be tailored to individual abilities and progress, encouraging active problem-solving. Tasks that are too simple may not stimulate sufficient learning and recovery, while overly challenging tasks can lead to frustration. Therefore, therapists should carefully adjust the difficulty of exercises to match the individual's current skill level, maximising recovery, and problem-solving abilities. Technology such as virtual reality (VR) can be harnessed to encourage a just right challenge by setting personalised boundaries for an individual's rehabilitation (Levin & Demers, 2021). Cognitive engagement and problem-solving are part of the motor learning process as suggested by the Challenge Point Theory of motor learning (Guadagnoll & Lee, 2004). Stroke patients may benefit from tasks that require them to think and strategize during their rehabilitation. Feedback helps the learner problem-solve the process of detecting and correcting errors while learning a more-skilled movement pattern (Levin & Demers, 2021).

Performance vs. Learning

In understanding the dynamics of motor learning, it is essential to distinguish between motor performance and motor learning and Schmidt & Lee (2019) provide a clear distinction. Performance represents the temporary execution of a motor skill at a specific moment, influenced by various factors such as fatigue, motivation, and environmental conditions. Conversely, learning denotes a relatively permanent change in an individual's capability to perform a motor skill over time, reflecting the acquisition and retention of the skill (Schmidt & Lee, 2019). While performance can fluctuate, learning is more stable and enduring. Therefore, in stroke rehabilitation, the focus should be on fostering motor learning, which involves both the acquisition of compensatory strategies and the gradual transition toward more normal movement patterns, ultimately enhancing the patient's long-term motor capabilities (Krakauer, 2006).

Feedback in Motor Learning

Maier and colleagues (2019) report on key principles of motor learning from literature that impact neurorehabilitation including the importance of meaningful feedback for enhancing motor learning. Knowledge of results (KR) and Knowledge of performance (KP) are key concepts in assessing and guiding a patient's progress. KR involves informing the patient about the outcome or result of a specific motor task, such as whether they successfully completed a movement goal. This feedback is essential for error detection and correction, motivating individuals to refine their motor skills (Schmidt & Lee, 2019). On the other hand, KP provides real-time information about the quality or characteristics of the motor performance during a task (concurrent) or just after the task is completed (terminal) (Levin & Demers, 2021). It focuses on the specific aspects of how a movement is executed, such as alignment, coordination, or posture. KP helps individuals understand the mechanics of their movements, enabling them to make adjustments for better performance. KR and KP work together to enhance motor learning. KR informs patients about task success, while KP helps them understand how to improve the quality of their movements. By providing both types of feedback, therapists can guide stroke survivors in optimising their motor skills, leading to better results and improved functional outcomes over time (Kleynen et al., 2020).

Motor Learning in Chronic Stroke

When acquiring or consolidating a skill, improvement in the skill requires ongoing practice (Schmidt & Lee, 2019). It is argued that neuroplasticity is normal in chronic stroke and therefore necessarily normal after spontaneous recovery post-stroke, therefore, motor learning may only be able to teach compensatory strategies (Krakauer & Carmichael, 2017). Krakauer & Carmichael (2017) suggest three ways that motor learning is implicated in chronic stroke rehabilitation; compensatory, increasing intensity (acuity) and residual normal action. For example when a patient attempts a task such as reaching using the weakened arm there is (1) a compensatory strategy to achieve the task arrived at by either self-exploration, therapist guidance or operant conditioning (the strategy taken may be trunk flexion due to difficulty in extending the elbow) (2) repeating the compensatory strategy many times gaining in skill (acuity) and (3) the patient can be encouraged, or even forced, to stop using the strategy and instead work on residual elbow extension (more normal movement pattern). All three of these kinds of learning may well be observed in a rehabilitation session to varying degrees. Some are likely undesirable (e.g., trunk flexion) and others more desirable (e.g., elbow extension). Therefore, motor learning should be harnessed to maximise residual normal movement while reducing undesirable compensatory movement and operant conditioning could help incentivise this via feedback (Krakauer & Carmichael, 2017).

2.1.4 Reducing Compensatory Strategies

As mentioned above there has been a focus in the rehabilitation field on function (activity) over impairment reduction. Patients who undertake reaching tasks with the affected limb will often resort to trunk flexion, a common compensatory movement (Roby-Brami et al., 2003) compared to a more restorative movement such as elbow extension – moving towards more normal movement patterns. Patients who use compensatory movements in their training may reach their goal, but in fact be exacerbating poor quality movements with long-term consequences such as joint contracture, learned non-use and subsequent pain (Pain et al., 2015). Thus, approaches which help to reduce compensation and encourage patients to spend more time in optimal movement patterns may lead to better long-term outcomes.

A common way to reduce compensation of the trunk is with a harnessing device as a physical restraint (Michaelsen et al., 2001; Wu et al., 2012). Auditory feedback with an alarm triggered by a pressure sensor on the back of a chair has also been used (Thielman & Bonsall, 2012; Thielman, 2010) and found to be more effective than a standard physical restraint (Thielman, 2010). Motion sensors in VR gaming environments (Foreman & Engsberg, 2019) and multimodal augmented feedback (Valdés & Van der Loos, 2018) have also been explored as a way to provide real-time feedback on trunk compensation.

However, there are few high-quality studies in this area of research. Two systematic reviews summarise several RCTs that have compared trunk restraint groups to control groups with no restraint (Greisberger et al., 2016; Pain et al., 2015). The results are not always clinically meaningful, but both reviews conclude that trunk restraint can improve quality of movement with some long-term gains up to 4 weeks found in one study (Michaelsen et al., 2006). Michaelsen and colleagues (2004) ran an RCT with 28 stroke patients and found that patients in the trunk restraint group showed less anterior trunk flexion, better elbow extension and joint coordination than the control group after training. Furthermore, there was evidence of retention in the trunk restraint group only with range of motion maintained 24 hours after the session.

Trunk restraint alone may not always be helpful, and clinicians need to use their clinical reasoning as there is a risk that the restraint may promote several issues: First, shoulder elevation may occur rather than a normal humeral activation when raising the arm. Second, when extending into forward reach protraction or abduction of the scapular instead of elbow extension, and third abnormal coupling of the shoulder and elbow where the humerus rotates too much with poor synergies (Pain et al., 2015). These further compensatory movements can interrupt recovery and lead to shoulder impingement pain (Timmons et al., 2012). The synergistic movement patterns (i.e. abnormal coupling of the shoulder and elbow) are undesirable in rehabilitation contexts, and therefore a goal of training should aim to reduce these (Liu et al., 2013). However, most current research has focused on reducing trunk flexion in patients, rather than other compensatory strategies. The kinetic and kinematic data is often collected but not used as feedback for patients, rather the data is used to analyse and further understand compensatory strategies (Liu et al., 2013). Patients may benefit from having real-time feedback on multiple compensatory strategies beyond that of trunk flexion and the current thesis aims to investigate this. In conclusion, reduction of undesirable compensatory movements may result in better quality more efficient movement patterns similar to those pre-stroke.

2.1.5 The Role of Motivation

As discussed, stroke patients with paresis need to undertake high dose and intensity and this requires a lot of will power. Motivation can help patients undertake recommended exercises away from the therapist to consolidate and keep up their rehabilitation goals and may be on their own in the home environment or in self-directed times on stroke units. One approach that attempts to increase motivation is that of the gamification of rehabilitation (Wang et al., 2017a). Companies and researchers are designing specific rehabilitation computer games using systems such as the Nintendo Wii (Karasu et al., 2018) or custom VR (Dias et al., 2019) that give rewards (scores and gameplay) to encourage a patient to undertake high dose exercises. However, there is an issue as patients in a survey study have described the stroke-specific rehabilitation games as boring with a preference for existing higher quality commercial games (Hung et al., 2016). These preferences may well change as rehabilitation companies build more high-quality games that can retain motivation for the long term (Krakauer & Carmichael, 2017). A second approach to increase motivation could be to undertake exercise with music as it lends itself well to movement providing a temporal framework for exercise (Magee et al., 2017). While listening to music stroke patients may be able to perform physical exercise for longer with less perceived effort as has been demonstrated in sports science (Karageorghis, 2013; Priest & Karageorghis, 2008).

2.2 Technology-Enabled Approaches to Stroke Rehabilitation

Emerging digital health technologies are transforming traditional rehabilitation practices with high acceptance levels among patients and they are reported to work well in combination with conventional therapies (Ballantyne & Rea, 2019). These tools aim to increase dose, intensity, quantification, personalisation, and accessibility of evidence-based therapies (Bok et al., 2023). Technology also has the potential to collect large amounts of detailed data (such as kinematic and performance metrics) that could help improve understanding of post-stroke recovery, enhance diagnostic tools, and lead to more effective treatment methods (Proffitt & Lange, 2015). There are a broad range of technologies that have been used in stroke rehabilitation such as robotic devices (Bressi et al., 2020), virtual reality (Al-Whaibi et al., 2022), computer vision (Knippenberg et al., 2017), wearable sensors (Al-Mahmood & Agyeman, 2018), telerehabilitation platforms (Szeto et al., 2023), and more recently artificial intelligence and machine learning applications that have shown initial promise in stroke rehabilitation (Choo & Chang, 2022). However, there are still barriers to widespread technology adoption including lack of accessibility, usability challenges, and need for further studies (Lobo et al., 2022).

2.2.1 Robotic Therapy

The use of robotic devices in stroke rehabilitation has been a subject of ongoing research within the medical community. These devices offer the advantage of providing high-dose rehabilitation by offering assistance or resistance in movement tasks, thereby increasing the intensity of rehabilitation, as noted by Krakauer & Carmichael (2017). However, questions persist about the true impact of robotic rehabilitation on functional outcomes for stroke patients. One key advantage of robotic therapy is the ability to measure the improvement of movement quality by tracking kinematics of movement and the forces involved (kinetics) that cannot be captured in standard clinical tests, as highlighted by (Veerbeek, et al., 2017). This ability provides a unique insight into the subtleties of motor recovery that may not be apparent through traditional clinical assessments.

Early reviews by Huang & Krakauer (2009) and Prange et al. (2006), suggested that robotic rehabilitation can reduce impairment but that it has minimal impact on functional outcomes. Furthermore, a comprehensive systematic review and meta-analysis by Veerbeek, et al. (2017) found no clear evidence that robot therapy provided more significant functional improvements compared to usual care or no treatment. These findings raise doubts about the utility of robot therapy in routine stroke rehabilitation.

However, recent reviews have introduced a more nuanced perspective on the potential benefits of robot therapy. In a Cochrane review conducted by Mehrholz et al. (2018), which focused on electromechanical and robot-assisted therapy, improvements were observed in activities of daily living, arm function, and arm muscle strength among individuals post-stroke.

Mehrholz and colleagues acknowledged differences in inclusion criteria, methodologies, and outcome measures when compared to earlier research, possibly explaining the disparities in reported effects. They underscored the need for further well-designed, large-scale studies to better assess the benefits and limitations of robotic therapy in upper limb rehabilitation.

Similarly, Johansen et al. (2023) conducted a systematic review that included analyses of 18 RCTs. Their findings indicated significant improvements in hand and arm function when compared to traditional therapy. However, it is worth noting that in the context of activities of daily living, a meta-analysis of nine studies yielded no significant effect size, in contrast to findings from Mehrholz et al. (2018). This discrepancy suggests that a cautious interpretation of these results is warranted.

A recent large RCT conducted entitled Robot Assisted Training for the Upper Limb after Stroke (RATULS) study contributes to this ongoing debate (Rodgers et al., 2019). RATULS compared robot-assisted training with enhanced upper limb therapy and usual care for stroke patients with moderate or severe upper limb limitations. The study's primary outcome was upper limb function success, measured by the Action Research Arm Test (ARAT) at three months. However, the results of RATULS did not support the use of robot-assisted training as provided in the trial for routine clinical practice in improving upper limb function after stroke.

In conclusion, the debate over the effectiveness of robot-assisted rehabilitation in stroke patients continues. While some studies suggest potential benefits in terms of reducing impairment and improving functional outcomes, others remain sceptical. The RATULS study (Rodgers et al., 2019) aligns with this ongoing discourse by providing evidence that robot-assisted training did not significantly improve upper limb function compared to usual care in stroke patients with upper limb limitations, highlighting the need for further research and a better understanding of the role of robotic therapy in stroke rehabilitation.

2.2.2 Virtual Reality in Stroke Rehabilitation

In virtual rehabilitation, users are immersed in simulated environments and interact with virtual objects through visual feedback presented via devices like head-mounted displays, projection systems, or flat screens (Weiss et al., 2006). Additional sensory feedback can also be provided, including auditory, haptic, proprioceptive, vestibular, and olfactory cues (Weiss et al., 2006). VR allows customised, engaging practice of functional skills matched to an individual's impairment level (Levin et al., 2015). Both immersive systems with headsets and non-immersive VR delivered through flat screens using systems such as the Xbox Kinect have been studied (Xavier-Rocha et al., 2020). A key advantage of VR is the ability to simulate real-world activities and facilitates repetitive, intensive, task-specific training at low cost and can be used in the home environment (Domínguez-Téllez et al., 2020).

Recent systematic reviews have found that VR is comparable to conventional therapy (Al-Whaibi et al., 2022; Laver et al., 2017). The largest body of evidence comes from the analysis of twenty-two trials in the Cochrane review from Laver and colleagues (2017) comparing VR to conventional therapy. There is some evidence that combining VR with usual care to increase the amount of therapy patients receive can achieve more improvement in functional outcomes, but the quality of evidence could be better (Laver et al., 2017). Further evidence from a meta-analysis of 21 RCTs found that combining conventional therapy with VR is better than conventional alone on functional outcomes (Fang et al., 2022). Another recent systematic review of 20 clinical trials found that VR was linked to improved UL motor function and quality of life (Domínguez-Téllez et al., 2020). Similarly, Chen and colleagues undertook a meta-analysis of 43 trials and found that VR supported therapy had significant improvements in motor function as measured by the upper limb Fugl-Meyer and range of motion (Chen et al., 2022).

VR shows promise but has some limitations, namely a lack of large, high-quality randomized trials demonstrating VR's long-term functional benefits and superiority over conventional therapy. There is large heterogeneity in VR protocols and systems, making comparisons difficult (Laver et al., 2017). Additional limitations include high costs and training requirements that restrict accessibility (Cavedoni et al., 2022), potential side effects like nausea with immersive VR (Weiss et al., 2006), and usability challenges where the equipment is not necessarily accessible to individuals with stroke (Proffitt & Lange, 2015). Isolation during VR therapy could also negatively impact social interaction (Pedroli et al., 2015). Further research is needed to address these limitations and optimise VR delivery to maximise functional gains.

However, VR also provides several advantages as an engaging platform to enrich traditional rehabilitation. It allows customised practice of repetitive, intensive tasks matched to an individual's abilities. VR can simulate activities not feasible in the clinic while providing real-time feedback to enhance motor learning (Foreman & Engsberg, 2019). The motivating nature of VR enhances patient engagement and adherence (Chen et al., 2022). When used at home, it enables remote monitoring and increased therapy doses (Vibhuti et al., 2023). In summary, VR creates motivating simulated environments for personalised intensive practice (Dias et al., 2019). While more research is required to guide implementation, VR holds promise as an adjuvant to augment conventional stroke rehabilitation.

2.2.3 Computer Vision in Stroke Rehabilitation

Computer vision and virtual reality represent two technology-enabled approaches being explored to enhance rehabilitation. Computer vision uses cameras and algorithms to visually analyse movements, enabling objective motion tracking (Knippenberg et al., 2017). In contrast, virtual reality immerses patients in simulated environments to engage in motor tasks, emphasizing experience through visualization and feedback. However, they can be complementary – virtual rehab can incorporate computer vision for motion tracking using pose estimation in real-time using commercial systems such as the Microsoft Kinect (Proffitt & Lange, 2015; Webster and Celik, 2014) and Leap Motion controller (Gonçalves et al., 2022; Wang et al., 2017b).

Computer vision techniques like 2D pose estimation and 3D pose estimation have been applied in stroke rehabilitation for quantitative movement analysis. 2D pose estimation methods like OpenPose (Cao et al., 2017; Papandreou et al., 2018) and PoseNet (Kendall et al., 2015) use single camera views and deep learning to estimate joint positions and model skeletal motion in 2D space. While accessible with standard cameras, occlusion can often limit accuracy, therefore researchers are working on new approaches to rearrange human skeleton joints generated by RGB (red, green, blue) image-based 2D skeleton recognition algorithms, such as OpenPose with an aim to produce a full 3D estimation output with a key aim to improve 3D estimation from 2D joints (Maskeliūnas et al., 2023).

3D pose estimation typically relies on multiple cameras or depth sensors to reconstruct 3D joint coordinates and kinematics in real-time. This requires more specialised hardware with the most common markerless tracking being the Xbox Kinect that uses an infrared camera and depth sensor to estimate 3D movements in real-time (Knippenberg et al., 2017; Xavier-Rocha et al., 2020). Studies have demonstrated that computer vision can assess arm kinematics during activities of daily living in stroke patients with accuracy comparable to clinical motion capture systems (Webster & Celik, 2014).

Beyond pose estimation, computer vision can also detect compensatory movements and a recent systematic review reports on the use of real-time and offline videos for clinicians to rate compensation levels (Wang et al., 2022). Three compensation types are reported in the review that successfully reduce compensation using markerless technology: trunk flexion, shoulder elevation and elbow abduction using markerless technology with machine learning algorithms to detect compensation. However, clinical integration remains limited pending more reliability testing. Furthermore, there are very few RCTs and often small sample sizes with a substantial variability of study protocols and therefore results need to be taken with caution.

Markerless systems like Microsoft Kinect use computer vision for affordable motion tracking but have limitations in accuracy due to occlusion, and hardware having to be in a specific location (Webster & Celik, 2014). Other pose tracking camera technologies also have limitations based on lighting, camera angles and occlusion (Chen et al., 2019). Considerations around difficulty adjustment and integration into clinical practice warrant further research. Overall, computer vision and motion capture technologies show promise for augmenting stroke rehabilitation through quantitative movement assessment and feedback and despite current limitations, computer vision is a promising technology to enhance stroke rehabilitation.

2.2.4 Wearable Sensors in Stroke Rehabilitation

Wearable sensors like inertial measurement units (IMUs) are increasingly being used in stroke rehabilitation and assessment to quantify upper extremity movement and function objectively (Carnevale et al., 2019; Martino Cinnera et al., 2023). IMUs are non-invasive tools that can be easily integrated into garments, strapped onto body segments (van Meulen et al., 2015), or embedded into devices like instrumented gloves (Lin et al., 2017). These typically contain accelerometers, gyroscopes, and sometimes magnetometers to provide motion data difficult to capture through observation and traditional assessments.

Studies using IMUs show they can accurately measure joint angles, range of motion, and arm orientation during clinical and daily living activities, comparable to sophisticated laboratory systems like optical motion capture (Bai et al., 2020). Additionally, IMUs provide movement quality metrics like smoothness, compensation, and symmetry not given by clinical tests alone (Hesam-Shariati et al., 2019). Home monitoring with wearables allows assessment of real-world arm usage compared to one-time clinical evaluations (van Meulen et al., 2015). Therefore, wearable IMU sensors are useful tools to obtain clinically meaningful kinematic data on post-stroke motor function. Their ability to objectively quantify movement quality and arm use, even outside the clinic, can support remote monitoring and assessment of patients (Burridge et al., 2017).

However, two recent systematic reviews assessed the effectiveness of wearable technology, including inertial sensors, for upper limb rehabilitation after stroke. Parker et al. (2020) included 11 studies (354 participants) testing wearable devices like functional electrical stimulation systems and robotic gloves. The methodological quality was limited and only 1 study found significant improvements in arm function compared to controls. Cinnera et al. (2023) reviewed 35 studies using inertial sensors to quantify arm movements and identified moderate correlations between sensor-based assessments and clinical scales. However, small sample sizes, heterogeneity in protocols, and lack of sensitivity data limited conclusions. In summary, insufficient high-quality evidence has been found to determine the efficacy of wearable technology for improving post-stroke upper limb activity and participation at this time, warranting larger, more robust clinical trials utilising appropriate methodologies.

2.2.5 Telerehabilitation & mHealth in Stroke Rehabilitation

Telerehabilitation utilises technologies to provide remote access to rehabilitation services. This approach can increase accessibility for patients with mobility limitations or those located far from clinics and allows therapists to monitor patients remotely (Sarfo et al., 2018). mHealth is closely related to telerehabilitation and includes the use of mobile devices and wearable sensors to monitor patient health and provide care remotely (Nimmanterdwong et al., 2022). mHealth tools such as educational apps, activity trackers, and mobile therapies can facilitate accessible stroke rehabilitation and management.

For example, a recent systematic review found that mobile app types which mimicked principles of effective face-to-face therapy and education had the greatest benefits for stroke recovery (Szeto et al., 2023). Another systematic review and meta-analysis found that home-based upper limb telerehabilitation programs were superior to conventional therapy for improving arm function and patients' perception of arm recovery (Toh et al., 2022). While personal smart technologies also show potential for improving outcomes in adults with acquired brain injuries, more research is still needed on their efficacy and implementation (Kettlewell et al., 2019).

Overall, early research indicates telerehabilitation and mHealth tools hold promise for increasing accessibility, enabling remote monitoring, and complementing in-clinic stroke rehabilitation. However, more robust evidence on their efficacy, feasibility, and optimal implementation is still required.

2.2.6 Artificial Intelligence and Machine Learning in Stroke Rehabilitation

There is growing interest in harnessing artificial intelligence (AI) and machine learning (ML) to augment technology-enabled approaches for stroke rehabilitation. AI systems demonstrate intelligent behaviours like learning and decision-making to assist in rehabilitation (Letham et al., 2015). ML algorithms automatically learn from data to make predictions for more adaptive treatments (Jordan & Mitchell, 2015).

Machine learning techniques used in stroke rehabilitation can broadly be categorised into supervised, and unsupervised approaches. Supervised learning involves training models using labelled data where the target outcomes are provided (Imura et al., 2021). Machine learning algorithms like regression and neural networks learn the relationship between inputs and outputs from example label-input pairs. This enables models to predict predefined outcomes or classes for new data. Supervised learning is useful when rehabilitation goals can be clearly specified. In contrast, unsupervised learning analyses unlabelled data to find hidden patterns, groupings, or representations without external classification (Mainali et al., 2021). Unsupervised learning is often used for exploratory analysis when the outputs are unknown.

Clustering algorithms like k-means are common unsupervised techniques. Unsupervised learning can reveal subgroups and trajectories within complex rehabilitation data.

One emerging form of supervised learning is interactive machine learning (IML) (Fails & Olsen, 2003) which closes the loop between clinician and algorithm by enabling real-time human guidance to train models (Lee et al., 2020). Furthermore, IML can be used to support participatory design of accessible interfaces (Katan et al., 2015). Unlike static supervised learning, clinicians can provide input to refine the model based on each patient's evolving needs. This combines human expertise with data-driven learning. Interactive machine learning is a novel approach which allows clinicians to guide the learning process for more personalised and adaptive rehabilitation (Lee et al., 2020). In IML, humans provide real-time input to refine the underlying ML models. For stroke rehabilitation, this enables therapists to customise the system's intelligence as patients progress. IML combines human expertise with data-driven learning, allowing rapid development of tailored intelligent systems that adapt to individual needs. Selecting the appropriate ML approach depends on the rehabilitation application and whether defined outcomes exist for training.

Another application is the use of AI for automated movement tracking during exercises or activities. Convolutional neural networks (CNNs), a type of deep learning model, are well-suited for analysing image data. Systems like OpenPose leverage CNNs to estimate 2D skeletal poses from video, providing tracking of patient movements (Cao et al., 2017). The pose estimation data can then be input to ML models to detect compensatory movements or assess task performance (Wang et al., 2022). This enables continuous quantitative monitoring and feedback. Other examples include incorporating ML into robotic devices and virtual reality systems. Robotics are using ML to personalise assistance forces that adapt as patients improve (Badesa et al., 2014). Virtual reality combines simulated environments with ML algorithms customise difficulty to individual abilities (Vaughan et al., 2016). Beyond tracking and customised training, ML is also being integrated into telerehabilitation platforms for capabilities like remote patient monitoring, and outcome prediction (Chae et al., 2020).

Overall, AI, ML and IML are enabling key technologies like computer vision, robotics, and VR to be more adaptive, personalised, and quantitative. However, clinical validation and integration into workflows remain challenges. While more research is still required, intelligent technologies have potential to transform rehabilitation by leveraging data-driven insights.

2.3 Co-Creation and Iterative User Centred Design for Stroke Rehabilitation

The development of novel technologies and interventions for stroke rehabilitation has been enhanced through contributions from human-centred design approaches, including co-creation (Dobe et al., 2023), participatory design (Duque et al., 2019), rapid prototyping (Perri et al., 2021) and human-computer interaction (HCI) methods (Good & Omisade, 2019). Traditional expert-driven engineering methods often resulted in tools with poor usability and accessibility for patients (Battarbee & Koskinen, 2005). Methodologies that actively involve users throughout design and leverage human-centred techniques have become instrumental in creating optimised, patient-centric healthcare innovations (Palmer et al., 2019).

Recent reviews have highlighted inconsistencies in terminology and methodology related to co-creation approaches in stroke rehabilitation and healthcare more broadly (Dobe et al., 2023; Lim et al., 2020). Co-creation emphasises collaboration between stakeholders such as clinicians, researchers, stroke survivors and carers. Benefits include interventions tailored to user needs and improved adoption (Balatsoukas et al., 2019; Driver et al., 2020). Key co-creation methods in stroke rehabilitation include focus groups (Balatsoukas et al., 2019), individual interviews (Jones et al., 2021), workshops (Aljaroodi et al., 2017), and prototype evaluations (Olafsdottir et al., 2020). Engagement levels during prototyping vary from consultation to full partnership (Carman et al., 2013). Participatory design and rapid prototyping enable iterative optimisation of interventions via user feedback (Farao et al., 2020).

2.3.1 Co-Creation in Stroke Rehabilitation

Co-creation (also referred it as co-design and co-production) in stroke rehabilitation emphasises collaboration among various stakeholders, including researchers, therapists, stroke survivors, and healthcare professionals (Dobe et al., 2023). This collaborative approach recognises the wealth of expertise and perspectives each stakeholder brings to the table (Aljaroodi et al., 2017). Multi-disciplinary teams work together to co-create rehabilitation programs and tools that are both evidence-based and attuned to the unique needs of stroke survivors (Fusco et al., 2023).

2.3.2 Participatory Approaches

Co-design stems from participatory design foundations where users participate mainly by providing feedback on design iterations. Power and control still remains for the main with designers and developers and users have a consultative role (Palmer et al., 2019). Participatory approaches utilise generative workshops, prototypes, and real-world activities to elicit insights and feedback from diverse stakeholders. While participatory design takes user input seriously, co-creation often values users as equal partners with joint ownership in the process. Co-creation emphasises the full partnership between users, designers, developers, and other stakeholders (Mironcika et al., 2008) .

2.3.3 Rapid Prototyping for Iterative Design

The use of rapid prototyping incorporates user feedback (Farao et al., 2020; Zbyszynski et al., 2017) and often makes use of low-fidelity prototypes made of paper, cardboard or simple materials that allow for quick, flexible recreations of solutions to test concepts and refine details. Users can manipulate them on the spot during participatory sessions to shape innovations matched to their capabilities and needs (Sefelin et al., 2003). This *fail fast, learn quickly* approach aligned with patient availability constraints enables accelerated optimisation of designs (Perri et al., 2021).

2.3.4 Human-Computer Interaction (HCI)

HCI aims to understand the interactions between humans and computers by studying behaviours, attitudes, perceptions, and needs of users (Park & McKilligan, 2018). HCI provides analytical techniques to systematically evaluate and refine prototypes created through co-design (Cairns & Cox, 2008). Methods like heuristic assessments, usability testing, motivation and workload measures allow pinpointing issues impacting adoption (Park & McKilligan, 2018). Qualitative feedback reveals user perceptions while usage metrics quantify engagement and outcomes (Adikari & McDonald, 2006; Cairns & Cox, 2008). HCI drives refinement toward solutions offering optimal usability, accessibility, and experience (Adikari & McDonald, 2006). In healthcare contexts like stroke rehabilitation, HCI and co-design intersect to rapidly elicit user needs, co-create solutions via prototypes, and refine designs based on systematic testing and feedback (Khademi Hedayat, 2015). Furthermore, there is a growing interest in using artificial intelligence with HCI techniques in healthcare (Nazar et al., 2021).

In summary, co-creation, participatory approaches and HCI methods all contribute to creating stroke rehabilitation technologies through actively involving users. Further exploration of human-centred techniques would support the advancement of personalised, effective rehabilitation interventions.

2.4 Music in Stroke Rehabilitation

Music holds much promise in the rehabilitation context as it has direct links to the pleasure and reward circuits of the brain (Altenmüller & Schlaug, 2013; Blood & Zatorre, 2001) and can engage and drive movement with implicit rhythmic features (Thaut, 2013). Music can help in the rehabilitation of motor functions (such as gait or upper limb), language functions, cognitive functions, mood and quality of life (Sihvonen et al., 2017).

However, it is important to remain cautious as a systematic review assessing the effect of music listening on cognition and mood post-stroke (Baylan et al., 2016) and a Cochrane review assessing the use of music in acquired brain injury interventions for movement, cognition, speech, emotions and sensory perceptions (Magee et al., 2017) state that the evidence is not yet strong enough to provide recommendations for clinical practice. This is reflected in two other systematic reviews that come to different conclusions on the benefit of music based interventions for upper limb stroke rehabilitation. Van Criekinge et al. (2019) found no clear consensus across 12 studies for the benefit of sound-based interventions for upper limb rehabilitation due to the heterogeneity of the outcome measures used across the studies. In contrast Lousin Moumdjian et al. (2017) systematically reviewed 19 studies on the effectiveness of music-based interventions reporting positive effects on upper limb function, mobility, and cognition compared to controls. The mixed results from the reviews highlight the urgent need for more high-quality research in the field and that we need to remain cautious about the effect of sound based interventions for upper limb rehabilitation

This section of the review will focus on music using either passive listening or active (physically moving to music or playing musical instruments) followed by a summary of research into sound-based interventions such as auditory cueing and sonification (mapping of kinematics onto sound). Although the current thesis focuses primarily on motor outcomes a brief review of the impact of music listening is of interest to illustrate how music can impact both physical and cognitive aspects of stroke rehabilitation. The studies are all from a music medicine perspective and draw from the subdiscipline of music therapy termed Neurologic Music Therapy (NMT) that strives to develop an approach to music therapy based on neurological evidence (Thaut et al., 2015).

2.4.1 Music Listening

Numerous brain regions are involved in music listening (Stewart et al., 2006) and listening to music improves neuronal connectivity in specific brain regions of healthy participants (Zatorre et al., 2007). Passive music listening induces changes in the nucleus accumbens, limbic, paralimbic systems involving the amygdala, and the hippocampus (Brown et al., 2004). Several RCTs have assessed the effect of listening to music with stroke patients (Baylan et al., 2016) and self-selected music was found to significantly enhance cognitive function along with better verbal memory and focused attention in stroke patients compared to either a language or control group (Särkämö et al., 2008). Patients who listened to music over two months for 1-2 hours per day also experienced less depressed and confused mood than the control group. Furthermore, it has been found that stroke patients who listen to self-selected pleasant music can ameliorate unilateral neglect as compared to either self-selected unpleasant music or a white noise control (Chen et al., 2013).

2.4.2 Self Chosen Music

The choice of music for therapeutic interventions may be an important consideration, as familiar and favoured music can make rehabilitation more tolerable and enjoyable (Wylie, 1992). This may have explained some of the effects seen in the Särkämö et al. study (2008), as enhanced motivation from self-selected music could be a powerful driver of high dose rehabilitation. Unfortunately, there is a scarcity of studies that have evaluated patient-selected music despite the potential for the music to be more meaningful and rewarding to the patient than generic music (Sihvonen et al., 2017).

A prior study by the author and colleagues found that patients were motivated to undertake hundreds of repetitions per session when undertaking active forward-reaching exercises to their favourite self-selected music (Kirk et al., 2016). However, it is notable that there is a lack of research that systematically compares patient-selected music to researcher-selected music or other forms of control to assess any potential impact on rehabilitation outcomes. While it is currently assumed that self-selected favourite music could lead to superior outcomes in upper limb rehabilitation for chronic stroke patients, this assumption requires further investigation.

However, a recent systematic review and meta-analysis of 14 RCTs on chronic pain found that the effectiveness of music as an adjuvant for pain management appeared to be significantly enhanced when patients chose the music themselves as opposed to when it was researcher-selected (Garza-Villarreal et al., 2017). The results, derived from a subgroup analysis of 5 RCTs, indicated a considerably larger effect size (P = 0.02) when patients selected the music (5 RCTs, SMD -0.81 [-1.02, -0.59]) compared to when researchers made the selection (9 RCTs, SMD -0.51 [-0.65, -0.36]) (Garza-Villarreal et al., 2017). Additionally, a recent review suggests that music preference can influence exercise performance in healthy individuals through factors like motivation, mood, and perceived exertion, with intricate interplay between psychological and physiological mechanisms (Ballmann, 2021). This underscores the potential importance of involving patients in the music selection process for achieving better clinical outcomes, especially in the context of physical rehabilitation.

Nevertheless, more empirical research is essential because there are limited studies conducted using self-selected music in rehabilitation, and none with robust controls assessing the impact of self-selected music in upper limb stroke rehabilitation. Unlike researcher-selected music, which can be standardised across treatment sessions, self-selected music lacks uniformity. This lack of standardisation can make it difficult to control variables and compare outcomes across different patients or studies. Furthermore, patients have diverse musical tastes, which can make it challenging to cater to everyone's preferences. What one patient finds motivating and enjoyable, another may not, leading to potential variations in the effectiveness of self-selected music. Finally, in stroke rehabilitation heterogeneity in patient responses could be exacerbated and highlights the need for more comprehensive research in this field.

2.4.3 Music Supported Therapy

Music-supported therapy (MST) has been developed to target the physical aspects of stroke rehabilitation where gross and fine movements of the paretic arm are trained through playing musical instruments (Schneider et al., 2007). Motor learning principles are used in MST with high repetition of movement patterns like those used in constraint therapies such as CIMT. In the original study, Schneider and colleagues (2007) recruited participants with stroke to tap on a set of drum pads using their affected arm to trigger piano sounds from a major scale. Exercises progressed from single sounds up to well-known melodies such as "Ode to Joy". Patients also undertook exercises targeting fine motor skills by playing a digital keyboard with individual fingers progressing through from simple to more complex tasks. Fifteen thirty-minute sessions over three weeks of therapy improved motor skills in the paretic arm significantly more than in a conventional therapy control group. A follow-up study found similar improvements on the fine and gross motor skills and further, patients improved cortical connectivity and increased activation of the motor cortex (Altenmüller et al., 2009).

The improvements in motor skills gained from MST may be enhanced with active music making, with evidence for this assertion coming from a study where patients who used muted instruments showed less improvement than an active music group (Tong et al., 2015). Thirty-three stroke survivors without substantial prior musical training were randomised into two groups: an audible music group or a mute music group. The results showed significant differences between the two groups on the Wolf Motor Function Test (WMFT), both for quality of movement (p = .025) and time to complete tasks (p = .037). However, no significant between-group differences were found on the Fugl-Meyer Assessment (FMA) (p = .448). What the specific role of music is in motor learning needs to be better understood. The mute group in the Tong et al. study was potentially less motivated to undertake the repetitive task training and there is evidence that an increase in motivation can boost motor learning (Colombo et al., 2007). Therefore, improvement in motor skill could be due to the motivational qualities of music rather than the auditory music feedback guiding motor learning (Van Vugt et al., 2016). A study from van Vugt and colleagues (2016) suggests that the immediate auditory feedback when playing a musical instrument may not be as effective as jittered feedback (an auditory delay that disrupts error-based learning without patients being aware of it). The finding is counter to the hypotheses that the immediate time-locked auditory musical feedback gained from playing musical instruments may be the primary driver of learning (Altenmüller et al., 2009). Overall, the specific role of music elements in motor learning requires further study.

2.4.4 Possible Mechanisms

MST may be more effective than conventional physiotherapy without music, but it is unclear what mechanisms could account for this; they may be due to motor, cognitive, and emotional mechanisms (Sihvonen et al., 2017). As previously mentioned, motivation may be a key driver but the underlying mechanisms are poorly understood (Zatorre et al., 2007). If the reward of taking part in rehabilitation with music leads to increased practice, then other mechanisms may not be as important (Schaefer, 2014). Neuroplasticity may be a critical mechanism in music making that can be equated to enriched environments in animal models where recovery at the behavioural and neurobiological level is heightened (Baroncelli et al., 2010). Two studies were undertaken to assess the role of plasticity in MST (Amengual et al., 2013; Grau-Sánchez et al., 2013) with reports of enhanced motor cortex activation compared to controls. Furthermore, there is a suggestion that auditory-motor coupling could lead to an improvement in stroke patients'motor function (Amengual et al., 2013). Rhythmic entrainment (our ability to synchronise with the beat of the music) has also been linked to strong activations of the auditory and motor regions of the brain (Zatorre et al., 2007) and forms the basis of rhythmic auditory stimulation (Thaut et al., 1996) one of the most widely used approaches in NMT.

2.5 Auditory Feedback in Stroke Rehabilitation

Incorporating digital technologies with sound-based feedback is being explored in a growing field of movement sonification in healthcare, particularly for rehabilitation purposes

(Nown et al., 2023). Both rhythmic auditory cueing and real-time movement sonification hold potential as methods to provide augmented auditory feedback during rehabilitation exercises. This section will summarise key approaches using sound and music to improve outcomes in stroke rehabilitation.

2.5.1 Rhythmic Auditory Cueing

Rhythmic auditory cueing (RAC) is synonymous with rhythmic auditory stimulation and has been shown to significantly improve gait and upper extremity function in stroke rehabilitation (Thaut & Abiru, 2010). The theoretical motivation of RAC is rhythm as a powerful neurological stimulant that people can automatically associate with certain physical movements. RAC encourages entrainment to an external repetitive isochronous beat such as a metronome, recorded music with the tempo adjusted, a combination of metronome and music, or live music emphasising rhythms to entrain to. A meta-analysis compared ten studies with 356 individuals assessing gait (Yoo et al., 2016); large effect sizes were found in walking velocity (Hedges's g = 0.984), cadence (Hedges's g = 0.840) and stride length (0.760). Another more recent meta-analysis (Ghai, 2018) found that 9 studies using RAC had a medium effect on the Fugl-Meyer with negligible heterogeneity (g: 0.6, 95% C.I: 0.30–0.91, I^2: 10.7%, $p > 0.05$). These findings highlight that RAC may not be as effective for upper limb rehabilitation and is corroborated by a Cochrane review that suggests music interventions may be beneficial for improving the timing of upper extremity function but found no evidence that RAC benefits range of motion (Magee et al., 2017).

However, there were only two studies included in the range of motion analysis and an RCT from Jeong and Kim (2007) found that participants in the experimental group gained a more extensive range of motion and flexibility after using rhythmic auditory stimulation (RAS) synonymous with RAC in a community exercise programme. Furthermore, the participants in the experimental group had more positive moods and reported increased frequency and quality of interpersonal relationships compared to usual care (Jeong & Kim 2007). There is a suggestion that RAC is at least as effective as CIMT (van Delden et al., 2013); 60 patients undertook 18 hours of therapy over six weeks randomised into either modified CIMT, modified bilateral arm training with auditory cueing, or dose-matched conventional therapy. The Action Research Arm Test was the primary functional outcome measure, and no differences were found between the groups. This is an interesting finding as when treatments are matched on dose, the outcome is equivalent which implies that dose and intensity may be the key mechanism to motor improvement.

2.5.2 Real-time Movement Sonification in Stroke Rehabilitation

Movement sonification is an emerging technology-based approach that uses auditory feedback to augment rehabilitation exercises. A recent mapping review undertaken by Nown et al. (2023) categorised and analysed real-time movement sonification systems in the literature to elucidate design trends and considerations. The review found substantial diversity in system configurations highlighting a need for more standardisation in the field. However, characterising attributes of existing systems provides valuable insights to inform future sonification design tailored to rehabilitation needs. Key findings included reviewing the motion tracking technologies used, like inertial sensors and camera systems, each with various trade-offs. Additionally, the review examined how physical motion parameters are mapped to sound features. Common strategies included linking position to pitch and velocity to loudness to provide real-time auditory feedback on the movements being performed.

Movement sonification has shown potential benefits for improving arm coordination, smoothness, and control after stroke (Scholz et al., 2016). The augmented auditory stream can enhance motor awareness and learning by engaging multisensory areas of the brain (Schmitz et al., 2013). However, many questions remain regarding optimal sonification design and implementation factors. A study by Nikmaram et al. (2019) examined musical sonification as a supplement to stroke rehabilitation. Patients performed sequenced arm movements, with a treatment group receiving real-time sonification of their motions. Controls had matched training without sound feedback. Results showed minimal clinical improvements with sonification versus conventional therapy alone, though motion tracking data indicated potential smoothness benefits. Exploratory analysis suggested sonification may increase brain connectivity on the impaired side. Overall, this initial study provides some evidence that musical sonification could be a feasible, engaging addition to traditional neurorehabilitation warranting further research; however, clinical impacts were limited, and low-cost tracking utility remained unclear.

In summary, real-time movement sonification for rehabilitation including technology approaches and sound mapping strategies, while promising, require more high-quality research and evidence for clinical adoption. Sonification tools may be able to enhance patient engagement and outcomes through customised auditory feedback that can be calibrated to suit individual recovery needs.

2.5.3 Auditory Feedback to Reduce Compensatory Movements

A novel approach to stroke rehabilitation is where movements are mapped onto sound facilitating real-time auditory feedback helping patients become aware of their movements (Schmitz et al., 2018). There is only one strategy that has used auditory feedback to reduce compensation in stroke patients and this focused on one compensatory movement – trunk flexion (Thielman, 2010). This feedback was a simple auditory alarm triggered from a pressure sensor on the back of a chair. The series of auditory feedback studies (Thielman & Bonsall, 2012; Thielman, 2010) and were successful but no data was collected regarding participants motivation levels.

No studies have used real-time auditory feedback for other compensatory strategies in upper limb rehabilitation such as shoulder abduction or to reduce the abnormal coupling of shoulder and elbow such as those listed by Pain et al. (2015). Furthermore, no studies have used self-selected music as a motivational signal to reduce compensation. Other types of feedback such as visual stimuli have been used to reduce compensatory strategies, but auditory stimuli could be highly effective and permit patients to pay closer attention to their own movement without having to look at a screen while they exercise.

There is likely an advantage to using auditory feedback over a physical harness to reduce trunk flexion. Patients can still activate their compensatory muscles to some degree and strain against the harness in a traditional trunk restraint. Furthermore, forcibly restricting the trunk with a harness is suggested to have poor carryover once the restraint has been removed (Thielman & Bonsall, 2012). In contrast with auditory feedback, the patient must be aware that they have compensated and actively engage their appropriate muscle groups to move their trunk back into a good upright posture to stop the feedback. Thus, auditory feedback provides a powerful way of working towards more efficient movement in two key ways; first there is a chance there is faster learning and secondly there could be longer-term retention of motor learning.

2.6 Conclusion

This literature review has discussed current approaches to upper limb rehabilitation after stroke highlighting how reducing impairment through minimising compensation may improve long-term outcomes (Levin et al., 2009). High-intensity, high-dose practice can drive neuroplastic changes in chronic stroke (Daly et al., 2019; McCabe et al., 2015). Technology-enabled methods like virtual reality, wearables, and computer vision provide opportunities to increase rehabilitation accessibility, intensity, measurement, and personalisation (Laver et al., 2017; Parker et al., 2020). Interactive machine learning is an approach that allows clinician guidance of algorithms toward customised treatments is a novel approach that allows clinician guidance of algorithms toward customised treatments (Lee et al., 2020) but requires more research in stroke rehabilitation contexts. Auditory feedback shows promise for improving movement quality (Schmitz et al., 2018) and patient-selected music feedback may further motivate patients to undertake high dose rehabilitation (Kirk et al., 2016). However, few studies have explored real-time auditory feedback to reduce compensation and improve reaching quality in chronic stroke. This represents a gap in the literature and a novel approach that is the primary focus of this thesis. In summary, this review highlights key areas needing further research specifically using real-time auditory feedback such as patient-selected music to promote motor re-learning and reduce compensation in chronic stroke rehabilitation. Supervised machine learning guided by clinician input is a promising yet understudied approach for creating personalised, adaptive treatments. To begin addressing gaps in translating theory into practical applications this thesis investigates the potential of music-based auditory feedback with computer vision and interactive machine learning tools.

CHAPTER 3: FORMATIVE RESEARCH DEVELOPMENT @ QUEEN SQUARE

3.1 Introduction

This chapter documents an iterative and interactive process of exploring the use of music as an aid for stroke rehabilitation. A collaborative approach was crucial to developing and implementing a full NHS protocol and bespoke system for upper limb stroke rehabilitation. The research documented in this thesis took place on the Queen Square Upper Limb (QSUL) neurorehabilitation programme, an intensive upper limb programme where service users undertake physical activities for 6 hours per day, five days a week for three whole weeks, totalling 90 hours (Kelly et al., 2020; Ward et al., 2019). There is a focus on high dose and intensity alongside quality of movement on the programme. While on the programme, educating service users about key issues is important, for instance, around overcoming barriers such as “learned non-use”, where service users tend to use the unimpaired arm, further weakening the hemiplegic limb. The three founders of the QSUL neurorehabilitation programme, Professor Nick Ward (Dr of clinical neurology and neurorehabilitation), Fran Brander, a consultant physiotherapist (PT), and Kate Kelly, a consultant occupational therapist (OT), provided expertise in the design and evaluation of the clinical work described in this thesis, building from earlier research (Kirk et al., 2016).

An initial knowledge exchange meeting and four workshops are described in this chapter. The knowledge exchange meeting and the first three workshops were carried out by key members of the QSUL programme alongside other research scientists. In contrast, human computer interaction (HCI) experts attended a fourth and final workshop. Consultations with staff helped to gain a deeper knowledge of key clinical issues in upper limb rehabilitation and better understand the existing provision of upper limb rehabilitation both on the QSUL programme and in the home environment. The knowledge sharing helped to investigate whether there was a role for novel technologies with an auditory component to build upon the existing rehabilitation that service users undertake. Outcomes from the consultations and interactive live demos in workshops provided a solid clinical and scientific rationale for the research by ensuring agreement on key assumptions underpinning the research.

A key element of this research was actively involving participants with chronic stroke early in the project in an iterative, user-centred design process to gather direct feedback and refine the auditory feedback system based on their experiences and preferences. Although participants with chronic stroke were not part of the initial conceptual workshops described in this chapter, multiple pilot sessions with service users from the QSUL neurorehabilitation program were conducted in parallel to evaluate and improve the system design. As detailed in Chapter 4, participants with chronic stroke provided input on the types of auditory feedback they preferred and their ability to perceive the feedback and use it to focus on their movement quality. This participatory research approach aligned with co-design principles and ensured that the end user perspective shaped the system development from an early stage. As the research with key stakeholders runs in parallel across Chapter 3 (primarily health experts) and Chapter 4 (primarily participants with chronic stroke), the next section describes the general methodologies employed to inform the design of a new upper limb stroke rehabilitation system. It provides a rationale for these methodological choices.

3.2 General Research Methods

3.2.1 Co-Creation Approach

A co-creation approach was adopted in this research, emphasising collaboration between different stakeholder groups, including clinicians, researchers, and participants with chronic stroke (Dobe et al., 2023). This collaborative methodology allowed expertise and perspectives from diverse areas to inform the system development. Furthermore, participatory design methods were utilised, given their focus on incorporating user input and feedback into rapid iterations of prototypes (Perri et al., 2021). The interactive workshops took a similar approach to those of Aljaroodi et al. (2017), enabling clinicians, researchers, and other stakeholders to actively shape the system design.

After the initial few workshops, in parallel, feasibility sessions attended by participants with chronic stroke offered evaluative user feedback to refine the system based on capabilities and preferences, aiding prototype evaluations (Olafsdottir et al., 2020). The participatory methods underpinned the workshops and end user testing sessions. Hands-on participation and rapid changes to working prototypes enabled accelerated optimisation and customisation aligned with user needs and preferences. As Farao and colleagues (2020) discuss, participatory techniques feed directly into the design and evaluation phases. Interactive sessions gathered input to shape prototypes, while flexible builds allowed rapid revisions between sessions to improve the system design and build. This *fail fast, learn quickly approach* (Perri et al., 2021) expediated system alignment to user capabilities by obtaining refinements and direct input from clinicians and end users. The rationale for using a co-creation methodology is that it used expertise from healthcare professionals and the lived experience of end users with chronic stroke. This allowed the distinct perspectives from clinicians and end users to inform system optimisations to better suit user preferences in a clinically relevant context.

In summary, a co-creation approach, and participatory methods offered stakeholders a framework to actively inform system developments. Iterative prototyping sessions with end users provided feedback to optimise the designs based on their rehab context and preferences.

3.2.2 Machine Learning Methods

A range of machine learning techniques were explored following the principles of interactive machine learning (IML), which in the context of this research, enables clinician guidance of algorithms toward customised treatments (Lee et al., 2020). IML supported participatory design through the workshops and hands-on bench testing of models (See Appendix 3-1).

Rationale for Machine Learning

The decision to employ machine learning software platforms, specifically Wekinator (Fiebrink et al., 2011) and OpenPose (Cao et al., 2017; Papandreou et al., 2018), was underpinned by their capacity for real-time tracking of multiple joint positions, as highlighted in previous research (Knippenberg et al., 2017). This capability was instrumental in capturing movement quality parameters for effective stroke rehabilitation. The tracking data generated through these platforms assumed a central role in the research, serving as the foundation for developing customisable auditory feedback mappings. These mappings were explored and refined throughout the workshops in the current Chapter, and in parallel tested directly with service users (described in Chapter 4), demonstrating their potential to enhance the rehabilitation process.

Interactive Machine Learning (IML)

The research methodology used Interactive Machine Learning (IML) (Fails & Olsen, 2003), drawing inspiration from prior work by Katan et al. (2015). This approach facilitated the integration of clinician input and personalised training, effectively tailoring the systems to cater to the unique requirements of individual service users. IML assumed a prominent role in the participatory workshops, enabling dynamic movement tracking and sonification adjustments based on real-time observations and expert clinician feedback. This iterative process of IML enabled the quantification of compensatory movements and provided invaluable feedback to guide participants towards attaining more efficient movement patterns. Consequently, the workshops primarily focused on mitigating common compensatory movements frequently observed in stroke survivors, leveraging the real-time tracking capabilities to deliver immediate auditory feedback.

Machine Learning Models

The methodology used in the current research was a hybrid, multiple-model approach where pre-trained machine learning models were used to manage different tasks, such as pose detection. Then these outputs were classified by another model that combined information from a range of sources. To achieve this, machine learning models built into the Wekinator platform (Fiebrink et al., 2011), including multilayer neural networks, linear regression systems (for tracking pose and mapping to outputs), and classification algorithms such as K-Nearest Neighbors (KNN) and Decision Trees were explored (see Appendix 3-1) to align with the specific movements relevant for upper limb stroke rehabilitation. The primary objective was to develop a system that could detect compensatory motions and provide real-time auditory feedback to facilitate rehabilitation. Importantly, markerless pose tracking camera technologies which were used in this research face challenges related to accuracy due to occlusion, hardware requirements, lighting, camera angles, and environmental conditions (Chen et al., 2019), and this has implications for the efficiency of the system which also required evaluation with users interactively.

In summary, the research methodology used IML to achieve precision tracking, flexible sound mapping, and clinician-guided optimisation of auditory feedback. This approach was designed to support the rapid prototyping methodology and was well suited to the proof-of concept research. Importantly, it was consistently guided by the participatory contributions from workshop attendees, as substantiated throughout the preceding sections.

3.3 Aims & Research Questions

The knowledge exchange meeting and workshops had two broad aims: 1) to encourage an open dialogue with experts in stroke rehabilitation, music psychology, motor neuroscience and human computer interaction in the co-design of a system to aid upper limb stroke rehabilitation and 2) to explore the potential use of sound as a rehabilitation aid via live interactive demos and discussion. The consultations with staff aimed to understand the QSUL programme approach to rehabilitation and how new technologies could be used to aid upper limb rehabilitation. Three broad questions were addressed:

(1) What are the key clinical considerations for upper limb rehabilitation?
(2) What potential is there for novel technologies including the use of sound to aid upper limb rehabilitation?
(3) How can sound be used to promote movement quality in upper limb rehabilitation?

Overall, the research questions and the processes used to address them helped inform the co-design of a bespoke rehabilitation system that was iterated via live interactive demos described in detail in sections 3.4 and 3.5.

3.4 Methods

3.4.1 Participants and Setting

A total of 18 participants from a broad range of backgrounds attended research sessions between October 2017 and November 2018, including the current author who attended and led all sessions. The consultations with clinical experts and interactive workshops exploring potential system concepts aligned with early-stage proof-of-concept research rather than improvements to rehabilitation service delivery. Service users with chronic stroke were not directly involved in the consultations and early workshop phase as the aim was first to understand the clinical perspective and the broader rehabilitation context. However, not long after the first few workshops, service users took part in parallel sessions with staff in attendance for direct service user input. Four sessions were completed in meeting rooms at the National Hospital for Neurology and Neurosurgery and a final session in a research lab at Goldsmiths University of London. Clinical experts included five core members of the QSUL neurorehabilitation programme, including the founders of the programme: Professor of Clinical Neurology, Consultant OT, Consultant PT, Specialist OT, Specialist PT and an additional visiting consultant PT attended Workshop 2. Three researchers in the field of motor neuroscience: Professor of Human Motor Neuroscience, Reader in Motor

Neuroscience and a PhD of Motor Neuroscience Candidate. The two PhD supervisors, Professor of Music Psychology and Professor of Creative Computing, attended most sessions. Finally, Workshop 4 was attended by 6 additional HCI researchers: Professor of Media Computing, Professor of HCI, Associate Lecturer in Computing and two HCI researchers. Written informed consent was given by all participants, and ethical approval was obtained from Goldsmiths University of London (see Appendix 3-2 with co-design workshop sections covering participant information and consent in sections 5.2 and 5.4).

3.4.2 Materials and Procedure

Audio Recordings and Transcription

Audio recordings of the knowledge sharing meeting and all four workshops were transcribed and used to inform the research moving forward. The audio was transcribed using an automated online service Temi (https://www.temi.com/), prior to extensive corrections within their online portal using standard conventions for transcribing speech as recommended by ten Have (Vinet & Zhedanov, 2011). As the environment was noisy, with, at times, multiple conversations overlapping, this process was time consuming and required multiple iterations of the audio to ensure unfamiliar clinical terms and discussions were captured accurately.

Knowledge Sharing Meeting

The knowledge sharing meeting was convened with the primary goal of gaining valuable insights into clinical perspectives regarding upper limb rehabilitation and to explore the potential contributions of technology and sound in upper limb stroke rehabilitation. The initial meeting played a pivotal role in shaping the subsequent course of the research. It provided an in-depth understanding of the challenges and priorities within the realm of upper limb rehabilitation, particularly within the context of emphasising high-dose therapy and movement quality.

Workshop Structure and Overview

All four workshops included live interactive demo sessions using computer vision approaches to track movement of the upper limb. The workshops were designed to be progressive, with each workshop building upon the insights and knowledge acquired from the preceding ones.

Workshop 1: Introduction and Exploration

Description: Workshop 1 served as an introductory session, primarily focused on acquainting clinicians with the machine learning platform OpenPose (Cao et al., 2017; Papandreou et al., 2018). The main objective was to establish a foundational understanding of the technology and its potential applications in stroke rehabilitation.

Procedure: The workshop commenced with an introduction to OpenPose and the application of this for real-time tracking of upper limb movements. Participants engaged in open-ended discussions designed to encourage dialogue and exploration. They explored various aspects, such as the problems that the technology could address, the types of data that would be most useful, current methods of tracking service user progress, strategies to motivate them, potential sonification modes, and the customisability of the system. Workshop 1 aimed to establish a common knowledge base among clinicians and initiate the collection of preliminary insights. These insights serve as a foundation for the subsequent workshops and the development of the technology.

All subsequent workshops had live interactive demos prepared in advance running off an MSI GE72MVR 17.3" FHD Gaming Laptop running Ubuntu 16.04 with a Logitech Full HD 1080 webcam placed on an adjustable tripod. The machine learning platforms were used to collect and train movement data in real-time. Pure Data (https://puredata.info/), an opensource visual programming language was used to manage data flow and create interactive demo applications to map movements to sound. The sound could be manipulated to provide feedback as either discrete auditory signal (e.g., a single sample trigger activates when a movement was detected) or continuous auditory signal (e.g., as a participant moves the volume of the auditory signal is increased based on their elbow position). Participants who had their upper limb movements tracked in the demo sessions undertook various reaching exercises with sound-based feedback. The tasks and sounds prepared for the live demos were iterated on between workshops using a rapid design methodology permitting changes to take place directly in the workshops with clinicians' direct input.

Workshops 2 and 3: Interactive Demos and Prototype Testing

Description: Workshops 2 and 3 focused on the feasibility and effectiveness of the technology for stroke rehabilitation. These workshops featured interactive demonstrations and prototype testing using the machine learning platforms, Wekinator and OpenPose.

Procedure: Participants engaged in live interactive demos, where computer vision techniques tracked their upper limb movements in real-time. Sound-based feedback was provided based on their movements, with options for discrete (triggered by specific movements) or continuous (adjusted based on limb position) feedback. Participants performed various reaching exercises while receiving sound-based feedback.

Workshop 4: HCI Expert Evaluation

Description: Workshop 4 introduced a HCI perspective to the evaluation process by involving HCI experts. This session aimed to assess the usability and user experience of the technology.

Procedure: Similar to Workshops 2 and 3, interactive demos were conducted, but this time with HCI experts as participants. Their evaluations focused on usability, user interface design, and overall user experience as well as accuracy of the machine learning models.

Parallel Case Series with Participants with Chronic Stroke

Concurrently with Workshops 2 and 3, case series sessions were conducted with participants who had chronic stroke (documented in Chapter 4). These sessions allowed for the evaluation of the technology's effectiveness and usability in a clinical context. Participants with chronic stroke engaged in similar interactive demos and exercises, providing valuable feedback for system refinement and design improvements.

3.4.3 Analysis

A thematic analytic approach was taken to extract key themes that arose across the five sessions based on session transcripts. The analysis followed six key phases as recommended by Braun and Clarke (Braun & Clarke, 2006) as follows: 1) familiarisation of the data including the transcription process; 2) generating initial codes systematically working though all documents[1]; 3) searching for themes by combining codes; 4) Reviewing themes ensuring good data fit; 5) Defining and naming themes; 6) collecting and summarising examples from the themes. The approach taken permitted a flexible analytic approach using a combination of two key approaches recognised in qualitative research: theoretical ‘top down’ and inductive ‘bottom up’. This permitted the natural flow of problem solving and ideas that arose to be given equal weight to the questions and prior research undertaken by the author and founding members of the QSUL neurorehabilitation programme (Kirk et al., 2016). Thematic analysis was selected as the optimal approach because of its flexibility to blend top-down and bottom-up interpretation. This enabled research questions to steer higher-level analysis while also allowing inductive themes to emerge directly from the complex multi-session data. Further, it systematically identifies common thematic elements across large heterogeneous datasets. Alternative methods like discourse analysis, interpretative phenomenological analysis, or grounded theory were less appropriate for analysing the

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[1] NVivo v12 for Mac was used for all coding of themes.

content and structure of the multi-participant consultation and workshop transcripts in relation to the defined research aims.

Outcome measurements were not collected since the aims of the workshops were exploratory. However, threshold filters were provided in the software to calibrate in real-time to signal when compensatory movements were occurring. The primary outcome measure was the proportion of time spent in compensatory movements during the reaching tasks although this was not analysed in these sessions but discussed and explored in the live demos to be implemented in future lab-based experiments (see Chapter 5 and 6). The ability to calibrate feedback was operationalised by using the machine learning models to track specific compensatory movements in real-time, such as shoulder abduction and trunk flexion.

3.5 Consultations with Clinicians, Scientists and Researchers

3.5.1 Results

The five sessions raised a large number of considerations for the current research as well as implications for future research and broader uses of machine learning within the field of stroke rehabilitation. The breadth of language used across all five sessions is depicted in Figure 3-1 below. Six top-level themes were extracted from the data and defined as: 1) QSUL neurorehabilitation programme; 2) feedback for service users; 3) movement in stroke rehabilitation; 4) sound for stroke rehabilitation; 5) system design; and 6) research considerations and NHS protocol development. A selection of direct quotes are summarised in Table 3-1 to provide a description of the data. The implications from the six themes are then discussed in greater detail in section 3.5.

Figure 3-1. A word cloud created in NVivo 12 for Mac based on the 200 most frequent words across all sessions totalling around 10 hours of discussions. The most common word when allowing for stemmed words was "movement" with 360 occurrences.

Table 3-1: *Themes and illustrative quotes from consultations*

Themes	Illustrative Quotes
Theme 1 QSUL neurorehabilitation programme	*Q1: "It's about getting people [service users on the QSUL programme] more functional if they're able to be." – Consultant PT* *Q2: "The programme that is then designed for them [service users on the QSUL programme] is tailored to deal with those impairments in a way that then allows them to use their arm in function. So, we are treating impairments to get functional gain.*

	That's the goal. A big part of it is education." – Professor of Clinical Neurology *Q3: "Task specific repetition over and over is not a [complete] rehab programme, that is not, it is part of it [a rehabilitation programme]. You can't get away from task repetition." – Professor of Clinical Neurology*
Theme 2 Feedback for service users	*Q4: "They [service users on the QSUL programme] get hooked up on the scores which they struggle with you know but if they have feedback that you do make change over 3 weeks or 6 months, if they see that change whether it is qualitative or quantitative. That is actually quite helpful for individuals, and they like that, and it has been seen as a real drive for their motivation and their quality of life." – Consultant OT* *Q5: "I don't think we [therapists] go, 'No, not like that'. We would say like, 'Long arm.' Or we'll say, 'Reach up higher, higher go go go.' [positive verbal feedback]. We don't give them loads of 'No, no straighten your elbow tuck your elbow under'. [negative feedback], We don't do any of that." – Consultant PT*
Theme 3 Movement in stroke rehabilitation	*Q6: "But you want them [service users] to actively start to use their arm otherwise they're never going to get any arm anyway. So forward reach is a good one." – Consultant OT* *Q7: "[Y]ou can do functional tasks and do impairment training. That's what we do. So, you could take the impairment training and see what you can do with the quality of movement. It's not really about the functional goal always. You might not do the*

	functional tasks at the end, with this particular project." – Consultant OT *Q8: "So, getting people to do more repetitions of better quality. Better quality and varied repetitions to achieve the same functional goal would be a good thing. That's a good starting point." – Professor of Clinical Neurology*
Theme 4 Sound for stroke rehabilitation	*Q9: "But there's lots of different options. I mean it could be literally anything now you've got that data. So, it could be they're listening to their favourite tune. But as soon as they've done something that you don't want them to, it cuts out or it scrambles it or whatever, or they could be producing something that is only continuing while they're doing what is within the limits that are set." – Professor of Music Psychology* *Q10: "Because if we had too many wah wah [alarms] or whatever it…" – Consultant PT* *"It* ***wouldn't*** *actually have a positive effect." – Visiting Consultant* *"…it might stop them practicing." – Consultant PT*
Theme 5 System design	*Q11: "We're aiming ultimately towards function, but the point of this exercise, I wonder whether it would be possible to individualise it in the sense that you would define the worst movement, but what they can currently do and the optimum for them."– Professor of Clinical Neurology*

	Q12: "So, it's more important to get the arm, to get a template which is specific to the individual... personalisation." – Professor of Creative Computing *"I think so. To get their arm moving as best as their arm can." – Consultant PT*
Theme 6 Research considerations and protocol development	*Q13: "I think we'd love to be able to know what they're doing and influence what they're doing both in the amount that they're doing and the way they're doing it." – Professor of Clinical Neurology* *Q14: "[F]or this stage of study, you will want your outcome score to be quite proximal to what you think the thing [system] is doing. You know when you are at small scale proof of concept. And the bigger you get when you go: Look this thing definitely changes people's kinematics, in a really beneficial way. Now the question becomes a different one. Saying well: Does changing people's kinematics, to become more "normal", have an impact on their quality-of-life? That's a different question. Whereas what a lot of people do in the field, they'll go from the intervention to the quality of life type outcome, and they will miss out all the bits in the middle. So, if it doesn't work, you don't know why it doesn't work." – Professor of Clinical Neurology*

3.5.2 Summary of Themes

Theme 1: QSUL neurorehabilitation programme

A rehabilitation programme for service users with chronic stroke in the view of the Neurologist, Consultant PT and Consultant OT cofounders requires some core principles: namely individual tailored expert coaching from both PTs and OTs with a focus on education

(Kelly et al., 2020). The programme has two key approaches that overlap involving service users in problem solving and goal setting: 1) impairment training (working on strength and range of movement) addressed in PT sessions and using technology such as robotic arms, and 2) functional goals worked on in OT sessions addressing activities of daily living (ADL) such as cooking, cleaning and washing. The programme is tailored to help service users understand their individual impairments encouraging use of the affected arm in function. Increasing dose by getting service users to use their arm more in daily life is crucial to long term rehabilitation improvement. By showing service users what is possible they fully understand that they can use their affected arm in more daily tasks than they previously thought. This may involve overcoming barriers such as forgetting they can use their affected limb. Another way that service users are guided and supported is by using videos recorded directly on their personal mobile phones to record specific tasks. This helps service users gain awareness and consolidate their rehabilitation when they are back at home. An interesting point is that not all service users can achieve functional tasks initially – they may have severe weakness, and this is where impairment training is required to help improve strength and range of movement working towards function.

What happens post discharge?

Service users are sent home with specific tailored tasks and functional goals to do and have their follow-up assessments at 6 weeks and 6 months. Individual goals are used to encourage high dose for the affected arm in the home environment. The QSUL programme does not currently measure service users' level of engagement at home and they have no way to track how much service users may use their arm functionally. They are not sure what dose has been achieved or maintained post discharge. The staff are unsure about how much service users do at home and why a small proportion of the service users do not see progress. There is a real challenge for some service users who state they notice improvements in the affected arm but are still too weak to use their arm in functional tasks. In this case slide sheets are recommended to help the service user train at home to continue building up their strength moving towards functional tasks. But motivation tends to be low, and service users are unlikely to adhere to their prescriptions of these mundane tasks in the home.

Goal setting

Goal setting is an important part of the programme, and the goals must be meaningful to the service users. Goals include repetitive short-term “practical” goals such as typing and writing, to “aspirational” participatory goals such as eating out with family and friends. The service user peer group who was interviewed after attending the QSUL programme said they carried on being motivated and engaged in their goals (Kelly et al., 2020). However, the continuation of individualised goals is not monitored by the staff post discharge. An important point is that a service user can achieve a goal without undertaking any physical rehabilitation at all; for example, if a goal is to get to the corner shop a mobility scooter permits this to happen without any physical rehabilitation taking place.

Discussions arose considering ways that technology could help monitor and track the goals of service users and if that may be of interest to the QSUL programme. It was agreed that aspirational goals would not be good candidates for tracking and monitoring as they may not involve the upper limb significantly and are real-world and challenging to define[2]. Monitoring goals with technology either on the stroke unit or in the home would likely need to focus on the task training aspects of the goals where there is often a lot of repetition. It was highlighted that kinematics may not be relevant for some goal tracking where the movements may be undefined and highly individualised. However, kinematics could help to monitor the simple repetitive task training aspect of a goal where high numbers of repetitions are aimed for.

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[2] Example: a service user has their goal to get to the corner shop. Giving them a mobility scooter may help them achieve the goal, but this will not aid their physical rehabilitation.

Independent practice

A key part of the QSUL programme are timetables sessions of “Independent Practice”. These are unsupervised sessions but usually in full view of other service users and staff. Independent Practice tends to be varied sometimes incorporating impairment training and other times more functional tasks. However, the Consultant PT did make it clear there are times when there is a lot of task repetition.

Clinical assessments

A battery of assessments is taken on the QSUL programme at baseline when a service user arrives on the programme, at the end of their three week stay, at 6 weeks and 6 months. It was clear that the outcome scores of various assessments can be difficult to interpret and furthermore that at times service users and staff may perceive improvements that are not picked up in the scores. Two scenarios were mentioned: 1) staff may perceive changes that a service user does not believe are happening or 2) a service user thinks they have some improvements that are not evident in the outcome scores. In both cases tracking a service user’s movements may help provide evidence for even small improvements. There was discussion of the potential to use machine learning approaches on videos of service users or other real-time tools for assessment in clinical settings. This was deemed a big challenge but could be clinically useful for the wider field of stroke rehabilitation.

Theme 2: Feedback for Service Users

Therapist Feedback

Via the educational problem-solving approach used on the QSUL programme therapists are in a constant dialogue with the service users providing verbal feedback. The expert tuition is important for some service users. However, there is a risk that some service users may struggle at times because of cognitive overload caused by large amounts of verbal feedback. This is where auditory feedback was considered a potentially less cognitively demanding guide for movement. Furthermore, sound could provide a useful guide in the home where there is no way for service users to receive therapist feedback.

Visual Feedback

As mentioned previously, service users are given personal videos to practice their rehabilitation exercises at home. However, the Consultant PT was concerned that using videos in a more real-time way as visual feedback for rehabilitation could be cognitively too demanding in a similar way as too much verbal feedback. The use of video feedback could create cognitive load and detract from the service user focusing on their affected limb as they moved towards a target movement. This aligns with documented attentional and information processing deficits after stroke, with over half of survivors facing cognitive impairment (Leśniak et al., 2008). This was taken seriously, and the system was designed to require no screen use by the service users. There is some evidence that service users may have sensory overload when receiving auditory feedback combined with visual feedback (Thielman & Bonsall, 2012). Therapists expressed a preference for visual feedback to focus more on functional tasks where it would be obvious if a target is achieved, for example, picking up a cup or pressing a light switch.

Knowledge-Based Feedback

From the discussions it was clear many service users like tracking their progress via the outcome scores which allow them to monitor improvements using quantitative data. It is interesting to note that this knowledge of results feedback may be useful and requested by service users at all impairments levels, low, moderate, and severe.

Positive and Negative Reinforcement

Therapists will usually focus on positive verbal reinforcement when working directly with service users as there is a risk of demotivating service users if there is too much focus on what is “wrong”. As evidenced in quote 5 above (Table 3-1) there is a real focus on positive encouragement and pushing service users further.

Theme 3: Movement in stroke rehabilitation

Levels of Movement

Two broad levels of movement were identified during discussion: fine motor (movements using the affected fingers and hands) and gross movements (primarily forward reach and hand to mouth). There were three common movements most applicable to the majority of service users: 1) forward reach, 2) hand to mouth, and 3) hand and finger extension. These were considered as potentially useful to track with service users. The Consultant PT suggested that even just tracking the index finger could be a useful aid. Tracking fine motor tasks involving finger and hand extension was agreed to be technically challenging, however, but nonetheless worth considering. The importance of actively reaching was raised as well as forward-reaching tasks being a logical starting point for tracking. Furthermore, these were considered likely to be relevant to most service users. Two key movements were also noted as important to encourage: namely shoulder flexion and elbow extension, which came up regularly in the discussions as being beneficial for a large proportion of service users.

Movement Quality

Although the QSUL programme has a key focus on functional aims there are many routes to work towards that. The PhD research could focus on any position along this continuum from impairment training (examples include strength training, stretching and range of movement) up to full functional tasks and real-world ADLs. There was encouragement from all the QSUL founders to consider going beyond focusing on repetitions and thinking more about *how* service users move. The interest in focusing on movement quality and maintaining motivation when transitioning into the home environment was discussed, as was the fact that the QSUL programme cannot track what happens in the home.

Another key consideration that was deliberated is the importance of aiming for "efficient movement". The use of the term "efficient movement" was contentious due to how the term is used in rehabilitation (efficient implies that the movement is less effortful). It was agreed that a more suitable term than "efficient" when using auditory feedback in the current research could be "consistency" of movement quality, implying that service users had a current optimum quality that was their current best. It was agreed that an approach that would help service users consistently achieve high quality movement at their current optimum was a clinically useful and achievable goal.

When focusing on movement quality the PT explained it is important to understand this can be achieved by reducing poor quality movement such as compensatory movements. The most common compensatory movements are shoulder abduction, shoulder elevation and trunk flexion. These compensatory movements are usually triggered due to what are termed synergistic patterns of movement or sometimes "abnormal coupling". These are unhelpful flexor synergies that include shoulder abduction, flexion of the elbow, and supination of the forearm. The Specialist PT stated that the opposite of synergistic movement in a clinical context is selective movement which is achieved by moving service users out of synergistic patterns of movement. Ideally service users should move with the best quality movement they can achieve. Increasing the efficiency of a service user's movement can be achieved by de-weighting (using an arm support to remove gravity) discussed at length across the sessions. This can be achieved using slide sheets or more advanced arm supports to remove the effect of gravity on the affected arm. De-weighting can help service users move out of synergistic flexor patterns of movement. It was agreed assessing the feasibility of using the de-weighting arms such as the SaeboMAS[3] or Saebo Mini used on the QSUL programme would be a useful endeavour.

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[3] The SaeboMAS range is available encouraging zero-gravity
https://www.saebo.com/shop/saebomas/

Theme 4: Sound for stroke rehabilitation

Auditory Feedback

A large proportion of time was spent discerning how sound may guide movement and movement quality was agreed to be the primary research focus. The versatility of auditory feedback was raised numerous times alongside the possibility of using discrete and/or continuous manipulations of sound to guide movement quality. The idea of constant monitoring with auditory feedback in real-world environments was discussed numerous times. The consensus was that negative reinforcement in the form of auditory alarm feedback should be carefully considered, as this may not have the desired effect of reducing bad movement patterns due to service users being irritated by the alarm sounds upon repeated occurrences.

Sound Types

The tempo or speed of sound-based stimuli, and how service users may move in time with music arose frequently in discussions. Tempo and entrainment to the beat of music was also suggested to be less relevant for the current research and the overall view was that it should be controlled for in any statistical analyses as it was hypothesised service users would slow their movements down with auditory feedback. However, it was suggested that a service user's baseline speed set to the tempo of the sound feedback could be achieved by selecting music at an appropriate tempo to encourage repetitive high dose reaching movements. Another possible use of sound discussed was to permit participants movement speed to dictate the speed of playback. The use of Musical Instrument Digital Interface (MIDI) based sound was suggested as it could make manipulations of the sound easier to track and change in quantifiable ways. However, discussions highlighted the inherent issues with the quality of sound from MIDI files, including that the sound timbre can lack consistency due to limited overall accuracy and variation in standard MIDI sound libraries when compared to most contemporary music recordings.

Strengths of Sound Based Approach

One strength to the sound-based approach that emerged from discussions was service users could undertake a rehabilitation task without the need for a screen – permitting more attention to the task. Moreover, the issues of cognitive load linked to verbal and video-based feedback were thought to be less of an issue using auditory feedback providing the feedback is simple. The use of music was considered as being a “motivational framework” for rehabilitation as in prior research (Kirk et al., 2016). The assertion that this motivation could lead to service users achieving more repetitions and higher dose with less perceived effort also arose.

Challenges in Sound Selection

A potential issue with using discrete sounds like scales and arpeggios or alarms was thought to be a risk of these types of sounds being irritating for service users if used for extended periods. Similarly, a sound-based system to help with the management of chronic pain was raised by the Consultant OT as being potentially off putting as she had tried it personally. Moving along to music could be an issue where movements are concerned if a service user is required to stay in a static position. There were a number of discussions around how much information to give a service user for them to understand how auditory feedback was linked to their movement. If there were multiple layers of sound relating to different movement parameters, it was agreed that service users could have difficulty in understanding and making use of the auditory feedback. It was agreed that service users would likely need to be explicitly told how the sound may change based on their movements in advance.

Theme 5: System Design

System Customisation

Customisation was considered important to permit rapid prototyping and testing in the workshops and service user user sessions. The choice of technologies (OpenPose, Wekinator and Puredata) were flexible choices permitting modifications to the software on the fly during live sessions. Furthermore, heterogeneity is common in service users with chronic stroke, hence individualisation of movement tracking was discussed at length and suggested to be a sensible approach aiming to be clinically useful. There were a number of advantages when considering machine learning for rehabilitation; namely the ability to track movement trajectories. Using computer vison models such as OpenPose as trialled in the workshops was deemed a good approach. Creating individualised movement templates was raised with reference to kinematic data and the potential of comparing the affected arm to the non-affected arm.

The role of therapists in helping to define relevant rehabilitation parameters for the systems used in the current research became an important consideration, particularly important when focusing on quality of movement. Another consideration was whether the system could not only track movement quality and repetitions but also adapt to the ability of the service user. An adaptive system could increase the challenge if a service user performed well or conversely reduce the system constraints if a service user was finding the task too challenging.

Theme 6: Research Considerations and Protocol Development

Initial assumptions underpinning the research were discussed and agreed by the clinical experts. Assumptions that high dose is important, and that music can provide a motivational framework were agreed to underpin the current research. More targeted formative assumptions about addressing the question of movement quality arose across all sessions with clinicians. It was agreed that auditory feedback could, in some way, guide service users'movements to ensure that they spent more time using their current best quality movement. However, there was an important acknowledgement that the system used would not be able to determine if a service user was moving beyond their current best quality without retraining the system to a new current optimum for the service user. Based on the system constraints service users were aiming to maintain their current optimum movement by reducing compensatory movements. The final primary research question was: Can participants with chronic stroke perceive and make use of auditory feedback (muting within self-selected music) to reduce compensatory movements in a seated active forward-reaching task? The question of more longitudinal research came up and highlighted a key challenge that this would require the system to recalibrate – or retrain between sessions to permit a new optimum for each service user to ensure an appropriate challenge as they may improve over time.

Research and protocol design were frequently discussed alongside considerations of ethics and inclusion criteria. Due to the nature of the QSUL programme it was agreed that a *within subject within session* design would be most appropriate to target initial questions around movement quality. As service users were on a very intense programme already the sessions needed to fit within the busy framework of the ongoing timetable. After revisiting the ideas multiple times, it became clear that tracking gross movements would be the most likely set of movements most applicable to the largest cohort of service users in the current research, and as such would be useful to track. Forward reach patterns and hand to mouth patterns of movement were suggested to be good candidates to focus on for the early-stage research tested directly with staff and service users on the ward prior to a final NHS protocol being deployed.

Issues of cognitive load came up frequently in the consultations, including how the therapists try and reduce this risk where possible. Ensuring that tasks are goal orientated helps to reduce the cognitive load. Another risk is that of physical fatigue for those service users with more severe impairments. The Consultant OT noted the importance of service users being able to rest for longer blocks than they trained during service user sessions. A further concern was that service users recruited while on the QSUL programme tend to be highly motivated and are already receiving a high dose with 90 hours of active therapy so setting up the research needed careful consideration.

Research outcomes were discussed, and it was agreed that an immediate measure of fatigue relating to the physical effort for each session would be required. There was an emphasis to keep the primary outcome measure targeted specifically to the study at this proof-of-concept stage. This meant the primary outcome was defined as the proportion of time in compensatory movements. There was a consensus that this approach was measuring movement quality by increasing the proportion of time that a service user could stay within optimal movement patterns.

3.6 Interactive Demo Sessions

3.6.1 Results

Over the course of the four workshops a system was co-designed. Key considerations for customisation and overall system design were discussed and iterated on directly in the workshops. A series of movements and sonification demos were run in the workshops. The outcomes from the iterative design process are summarised in Table 3-2. The exercises primarily focused around two fundamental gross movement patterns recommended during the initial knowledge exchange meeting: “hand to mouth” and “forward reach”. These movement patterns were chosen in line with skill acquisition literature, which emphasises the importance of task specificity and feedback for motor learning and neurorehabilitation (Kleynen et al., 2020; Levin & Demers, 2021; Maier et al., 2019; Schmidt & Lee, 2019).

To facilitate motor skill acquisition continuous and discrete sound mappings were systematically explored. These mappings were implemented across ten distinct tasks conducted with active workshop participants (see Table 3-2). It is worth noting that the first four tasks were specifically designed to increase dose and motivation, aligning with the principles of skill acquisition literature that advocate for providing adequate practice opportunities (Kitago & Krakauer, 2013). In these tasks, music was employed as both a motivator and a means of "rewarding" participants when they successfully achieved a target pose. Conversely, tasks 5 to 10 were crafted with a different objective in mind—namely, the enhancement of optimal movement patterns while mitigating compensatory movements. This approach was guided by direct input from the QSUL staff, taking into account the principles of motor learning that emphasise the role of feedback, particularly Knowledge of Performance (KP) and Knowledge of Results (KR), in guiding and optimising motor performance (Maier et al, 2019; Schmidt & Lee, 2019).

In Tasks 5, 6 and 7, feedback mechanisms, such as alarms and silencing of music, were integrated to discourage compensatory movements, specifically shoulder abduction. These feedback mechanisms align with the concurrent KP approach, as they provide real-time information about the quality or characteristics of motor performance during the task execution (Levin & Demers, 2021). Similarly, Task 8 sought to reduce trunk flexion by incorporating an alarm system, delivering feedback consistent with concurrent KP principles. Task 9 targeted the reduction of shoulder elevation, also employing concurrent KP by monitoring shoulder movement and providing negative feedback when participants exceeded predefined thresholds. Finally, Task 10, building upon the principles of concurrent KP and motor learning literature, employed self-chosen favourite music. However, this music was subjected to distortion, pitch alteration, and tempo variations if participants exhibited poor movement quality, emphasising the significance of concurrent KP feedback in facilitating real-time movement adjustments (Maier et al, 2019).

In summary, the tasks outlined in Table 3-2 align with the skill acquisition literature's principles of providing appropriate feedback, task specificity, and customisation for effective neurorehabilitation and motor learning. The design of these tasks aimed to promote both the quantity and quality of movement practice, reflecting the iterative process of co-design in collaboration with workshop participants and informed by skill acquisition literature.

Table 3-2: *Live interactive demos run with workshop participants*

Task/Demo number	Task / exercise	Rehabilitation Aim	Sound(s)	ML Models
1,2	hand to mouth	high dose / more repetitions 1. start pos. hand on table 2. reach to target object (jar or cup) 3. bring object to mouth 4. place object back at target 5. return to start position	audio samples 1: kick, snare, hi-hat • sound at each pose • triggering at a constant tempo 2: arpeggios (C maj triad) • notes mapped to poses • triggering at a constant tempo or only when target reached	3 linear regression models • trained to target poses using wrist (x,y) • record value = 1 at matching pose and value = 0 at other poses
3	hand to mouth	high dose / more repetitions reward hand to mouth poses as with demo 1 (same movements and poses)	coupled or layered sound • hear favourite music • samples from demo 1 trigger in time layering on top of the music	Same setup and training as demo 1 & 2
4	forward reach	high dose / more repetitions • reach forward and back to target (jar or cup)	piano audio samples • C maj arpeggio with octave added C4-C5 • notes linearly mapped from start to target pose	1 linear regression or NN • trained to target poses using wrist (x,y) • record value = 1 at target pose and value = 0 at starting pose
5,6,7	forward reach	reduce shoulder abduction • reach forward and back to target (jar or cup) • receive positive feedback if moving in optimum • receive negative feedback if compensating above an adjustable threshold	5: alarm sample • marimba tone • sounds if elbow moves out beyond the threshold 6: self-chosen favourite music • song plays if optimum movements • if elbow > threshold music stops at current **sample** (silence) 7: Alternative • or if elbow > threshold music **mutes** and continues in silence	1 linear regression or NN • trained to elbow (x,y) • record value = 1 with elbow held out ~ 15 cm (i.e. bad movement) • record value = 0 for three full reaches of optimum movement
8	forward reach	reduce trunk flexion • reach forward and back to target (jar or cup)	alarm sample • chime sound	1 linear regression or NN • trained to neck (x,y) and

		☐ receive negative feedback if compensating above an adjustable threshold	☐ sounds if trunk flexes above threshold	affected shoulder (x,y) ☐ record value = 0 for three full reaches of optimum movement ☐ record value = 1 while leaning forward by ~ 10cm
9	forward reach	reduce shoulder elevation ☐ reach forward and back to target (jar or cup) receive negative feedback if compensating above an adjustable threshold	same options as demo 6 & 7 ☐ no alarms were tried for this demo	1 linear regression or NN ☐ trained to shoulder (x,y) ☐ record value = 0 for three full reaches of optimum movement ☐ record value = 1 while holding shoulder up by ~ 5cm
10	forward reach	reduce shoulder abduction ☐ same as demo 5,6,7	self-chosen favourite music ☐ music plays in optimum movements 10: if elbow > threshold: music is filtered in possible ways: ☐ music distorts ☐ music pitch goes high ☐ music pitch goes low ☐ music tempo slows ☐ music tempo speeds up	same as demo 5,6,7

Note: ML = machine learning; NN = neural network

3.6.2 Summary of Demonstrator sessions

The interactive demonstrator sessions conducted during the workshops served as a critical component in evaluating and refining the Sonic Sleeve system. These sessions involved hands-on testing of various auditory feedback mappings during two key exercises: hand-to-mouth movements and forward-reaching exercises (see Table 3-2). They provided an opportunity for real-time system evaluation, guided by direct observations of user performance, expert clinician input, and the core principles derived from the QSUL neurorehabilitation program, as detailed in Theme 1 above.

Hand to mouth exercises

The primary rehabilitation aim of these exercises was to encourage more repetitions in stroke recovery. Participants were tasked with a sequence involving picking up a cup from a table, raising it to mouth height, and returning it to the table. To provide auditory feedback, linear regression models were employed, mapping specific wrist positions to discrete triggering of percussive samples or musical arpeggios. Findings from these exercises were crucial in guiding system design. Demo 1 used audio samples to provide feedback, where sounds were triggered at each pose. However, this approach lacked clarity and precision in feedback delivery. In Demo 2, arpeggios were introduced, with musical notes mapped to poses. Yet, simultaneous activations from parallel machine learning models led to difficulty in understanding and making use of the mappings. In Demo 3, samples were added on top of the music and were again challenging for the users to engage with. These findings prompted a shift towards simpler triggered audio samples in subsequent iterations, addressing the identified limitations and aligning with the principle of consistent perception in motor learning.

Forward reach exercises

The rehabilitation goal of the forward reach exercises was to reduce undesirable movements such as shoulder abduction, trunk flexion, and shoulder elevation, while encouraging optimal reach movements. Participants were required to reach forward to a target object (jar or cup) and then return to the starting position. Findings from these exercises had a significant impact on system design. The demos incorporated alarms or music to provide real-time feedback on optimal movements and discourage compensation. Demos progressively worked up to cover more compensatory movements. These demos demonstrated the effectiveness of using alarm sounds, marimba tones, and music to provide immediate feedback on movement quality. Adjustable thresholds were introduced to customise feedback for individual users. The development of a consistent feedback system was driven by the need to discourage compensation and encourage optimal movements.

Discrete vs. Continuous Auditory Feedback

Throughout the demos, both layered auditory stimuli and binary start/stop triggers were implemented across the tasks. However, observations and clinician input highlighted potential interpretation challenges arising from ambiguity associated with layered sounds. Consequently, it was determined that discrete on/off signals provided the clearest and most consistent perception for users, guiding the preference for binary feedback mechanisms in the subsequent design iterations. This decision was strongly influenced by the cognitive demands on users and their engagement with the feedback system.

The interactive demo sessions allowed for collaborative testing, troubleshooting, and refinement of auditory feedback signals, all in alignment with overarching motor learning principles. These insights served as a foundation for refining the Sonic Sleeve system, ensuring that the auditory feedback effectively guided users in improving movement quality while maintaining user engagement. Importantly, it should be reiterated that parallel sessions with end-users ran concurrently with Workshops 2 and 3, and these sessions provided invaluable feedback for system refinement. A more detailed exploration of these parallel sessions and their impact on system design is discussed in Chapter 4.

In summary, the iterative development of the Sonic Sleeve system was informed by the outcomes of these demo sessions. The transition to binary on/off feedback mechanisms, driven by user engagement and cognitive considerations, helped to refine the system design. This iterative and user-centric approach was essential in enhancing the system's usability and effectiveness.

3.7 Discussion

Over the course of consultations and live interactive demos six key themes were extracted and supported the development of a new rehabilitation system and protocol linking directly to the key research questions. Key outcomes from the initial knowledge sharing meeting and workshops helped to address the research questions around clinical considerations and use of novel technologies for upper limb rehabilitation. The primary outcome of interest from the consultations was that the current research should focus on quality of movement and that a protocol should have a primary outcome to measure movement quality specifically. The session identified two key problems to solve: First that of implementing and evaluating a system that would permit service users to have real-time knowledge of their movement quality during their upper limb rehabilitation; and second, that service users are not monitored at home with no ability to know if they are adhering to their prescribed program to achieve high dose or good quality movement. Therefore, a further consideration was to aim for a system that could transition into the home environment permitting service users to undertake rehabilitation exercises without a therapist needing to be present. There were a number of technical issues raised in the live interactive demos that helped to iterate new versions of the software and to select more appropriate machine learning models. As retraining was often required and neural networks took around two minutes to train each time this could be a potential barrier in busy clinical settings where time is scarce.

The outcomes of the consultations supported the argument that the intervention tasks did not have to be training a functional task directly, but they could focus initially on impairment training (i.e. simpler repetitive reaching tasks rather than aiming for full ADLs). By adapting functional tasks and taking the key components to make the movement simple to follow for service users, clinically useful rehabilitation could be achieved. There was consensus that reducing compensatory movements was a useful strategy to help service users become aware and focus on their movement quality. A broad range of sound to movement mappings were tested directly in live interactive demos and examples of continuous, discrete, and layered sounds were provided. Outcomes from the live demos suggested that binary auditory feedback signals may be most appropriate to guide service users into optimal movement. However, the use of binary vs. continuous signals needs to be assessed directly by service users with guidance from staff to help refine the system.

The focus on a knowledge exchange meeting and workshops ensured clinical relevance through the direct involvement of experts in stroke rehabilitation. The participatory elements also created tight feedback loops to quickly gather clinical and research insight on the prototypes through observation and expert user comments and feedback. However, some limitations stem from the relatively restricted involvement of a small number of clinicians and the lack of service user input in the early design phases. The findings may not generalise across heterogeneous stroke groups outside of the sample engaged. Lastly, prioritising clinical assumptions early on risked biasing decisions toward therapist perspectives rather than integrating service user priorities. The lack of inclusion of service users with chronic stroke in the initial knowledge sharing activities represents a limitation. Expanding involvement to include the service users with direct lived experience even earlier on alongside clinician guidance may have further strengthened the knowledge foundations informing system development. A truly collaborative co-design approach would benefit from incorporating both clinical and service user input across all phases. There was an inherent risk of bias by prioritising clinician assumptions early on before garnering service user input. However, the highly iterative process allowed user feedback to help mitigate this.

3.8 Conclusion

The five sessions provided the clinical expertise and oversight to ensure the scientific rationale for the research was sound and clinically relevant to service users. Tracking movements in real-time could be used as a rehabilitation aid to guide optimal movements for service users even when a therapist is not physically with a service user. The live interactive demos helped to test ideas with staff members in parallel to trialling the various types of sound feedback directly with service users in a series of case studies documented in the next chapter.

CHAPTER 4: SYSTEM DESIGN AND ITERATIVE CASE STUDIES WITH SERVICE USERS AND STAFF

4.1 Introduction

This chapter describes the process of iterative system and research protocol design with ten service users with chronic stroke. When designing and testing a system to deliver upper limb rehabilitation, it is important to do so with the service user's acceptability and usability in mind. There are key barriers to embedding assistive technologies into clinical practice, and improving the design of the systems is recommended (Hughes et al., 2014). This chapter explores the acceptability and usability of a new system for upper limb rehabilitation by undertaking 10 case studies conducted with the direct input of staff and service users on the Queen Square Upper Limb (QSUL) neurorehabilitation programme.

4.2 Aims & Research Questions

The sessions with service users had two broad aims: 1) To assess the technical development and feasibility of the Sonic Sleeve system, designed to provide real-time auditory feedback based on participants' upper limb movements, and 2) To establish a robust research protocol for conducting more extensive studies involving auditory feedback in upper limb rehabilitation. Three questions were addressed as follows:

(1) What sound feedback is preferred by participants with chronic stroke?

(2) Can participants with chronic stroke notice changes to sound based on their movements?

(3) What are the optimal number of movements and rest periods when using auditory feedback?

The three research questions provided valuable insights into user preferences, perception, and the optimisation of training regimens, contributing to the user-centred design and utility of auditory feedback systems for individuals with chronic stroke.

4.3 Method

4.3.1 Study Design

As described in Chapter 3, the study design employed in this research followed an iterative participatory approach, encompassing interactive machine learning (IML) workshops and concurrent feasibility case studies. It fundamentally prioritised user-centred development, placing the perspectives and preferences of participants with chronic stroke at the core of the auditory feedback system's design. This iterative approach, guided by the principles in the methodology (section 3.2), facilitated rapid system refinement in response to user feedback. Additionally, the feasibility studies running concurrently with the IML workshops ensured user input from service users and clinical experts. The emphasis was on qualitative insights, aligning with the research's exploratory phase, aiming to gain a deeper understanding of user experiences and preferences. This iterative and user-centric design approach subsequently informed the experiments documented in Chapters 5 and 6.

4.3.2 Participants and setting

Participants

The participants in this study consisted of ten individuals with chronic stroke who were enrolled on the QSUL neurorehabilitation program. Participants were recruited from among those receiving care through the program, and no specific exclusion criteria were applied to ensure a representative sample. The study sessions were conducted within the framework of service development activities as an integral part of the QSUL neurorehabilitation program. These activities aim to enhance the service users' quality of care. All sessions in the current study were conducted in treatment rooms on the stroke unit with one or two senior staff members in attendance to support and ensure all activities were relevant to the participants. This setting allowed for the seamless integration of research activities into participants' routine therapy appointments, minimising disruption to their care. In addition, the PhD researcher had a full NHS honorary contract to work directly with service users and staff on the stroke unit.

Ethical clearance for the research was obtained from the Goldsmiths University of London Ethics Committee (see Appendix 3-2 containing ethics forms for participant information and consent in sections 5.1 and 5.3). Written informed consent was obtained from all participants, and they were given ample opportunity to ask questions and seek clarification before providing consent. This approach ensured that the research activities were conducted in an ethical manner, aligning with the principles of transparency, respect for participants' autonomy, and adherence to ethical guidelines, even though personal data was not collected during the feasibility stages of the research.

Participant Recruitment

Service users were approached during their routine therapy appointments on the stroke unit as part of ongoing service development activities. Staff on the stroke unit informed the service users about the research aspects of the study and provided them with a participant information sheet (PIS) (see Appendix 3-2 section 5.1). Participation was entirely voluntary, and participants were assured that their decision to participate or decline would not affect their access to routine therapy services.

4.3.3 Materials and procedure

Motion Capture Setup

Tracking upper limb movement was a core requirement for providing real-time auditory feedback on quality of movement. A 2D webcam-based approach was selected to prioritise accessibility, ease of setup, and potential translation for in-home use. While more complex 3D motion capture options were considered, the priority was establishing initial feasibility. The system utilised a Logitech C920 webcam, capturing video at 1080p resolution and 30 frames per second. The webcam was mounted on an adjustable tripod with the camera positioned to capture the affected arm (either right or left) of each participant from an angle at either 2 o'clock or 10 o'clock, relative to their affected arm's orientation. This setup ensured optimal visibility for pose tracking during reaching movements, closely mimicking a therapist's natural viewing perspective. Additionally, it helped mitigate challenges related to occlusion and tracking accuracy. Video feed from the camera was mapped to open-source software OpenPose (Cao et al., 2017; Papandreou et al., 2018) to estimate 2D skeletal pose using machine learning. OpenPose outputs pixel coordinates of key joints, providing position tracking of wrist, elbow, and shoulder joints.

Technical Development

Based on the initial live demos with health experts, a system was iterated directly with service users with chronic stroke, focusing on sound-based feedback to reduce compensatory movements. Sonic Sleeve, the system developed for the current research, takes kinematic movement data from a 2D webcam using the open-source software OpenPose (Cao et al., 2017; Papandreou et al., 2018) and maps that data to provide real-time auditory feedback (see Figure 4-1). Four x, y pairs of co-ordinates are derived from the participants' affected limb: neck, wrist, elbow and shoulder. A machine learning (ML) platform, Wekinator (Fiebrink et al., 2011), is then used to record from each participant individually examples of i) forward reach movement (target), ii) trunk flexion, iii) shoulder abduction and iv) shoulder elevation (three forms of compensatory movement).

Figure 4-1: Basic Pipeline for Data. Pd = Pure Data; ML = machine learning

Three machine learning models were trialled: neural networks (NN), linear regression and K-Nearest Neighbors (KNN). NN and KNN models were used to record examples of the start position and end position of the target movement to track repetitions. Shoulder abduction, trunk flexion and shoulder elevation (three compensation types) were modelled using both NN and linear regression models by taking the relevant x, and y coordinate pairs. After each session with participants on the ward, questions addressing the development of the system and study protocol were answered in detail by the current author to iterate on system design and to improve the usability of the system: 1) Does the system work effectively?; 2) Do participants notice the error sonification?; 3) Can participants use this information effectively?; 4) Do participants express a preference for a specific type of feedback?; 5) What are the optimum number of movements and rest periods

System Testing

Additional system testing was carried out at regular intervals between the workshops and service user sessions by the author. The test results are listed in the table in Appendix 3-1 detailing the success and failure rates of various models listing the test aim, pre-processing, model constraints, algorithm used, sonification approach and a subjective rating of model success on a scale of 1-10 as a benchmark for model success. Various machine learning techniques were explored, as described previously in section 3.2.2 above. See the diagram in Figure 4-3 for details of the inputs and outputs for the system that were trained on combinations of wrist, elbow and shoulder joint coordinates extracted from the camera feed. Outputs were mapped to different forms of real-time auditory feedback using auditory parameters to convey movement quality information. Input data cleaning reduced noise and fluctuations, enhancing precision, as detailed in Figure 4-3. Recording examples of well-defined optimal movements was vital for preventing noisy data that led to feedback that was difficult to use. Overall, linear regression produced the most consistent outputs for real-time sonification based on observations in the user sessions and the test results mentioned above (see section 4.4.7 for further discussion on the evidence for linear regression use and the importance of system calibration and validation with therapist input). The most effective combination utilised separate linear models, data cleaning, and auditory manipulation with silence as feedback when thresholds were exceeded. These empirical findings directly informed the interactive machine learning training approach for the subsequent experimental studies described in Chapters 5 and 6.

Session Setup

The system was setup in advance, ready to track participants' movements. The sessions were run off an MSI GE72MVR 17.3" FHD Gaming Laptop running Ubuntu 16.04. with a Logitech Full HD 1080 webcam placed on an adjustable tripod to capture participants' movements. Participants and staff took an active role in feeding back on their ideas about the use of sound and music to guide movement quality. The researcher led the sessions with live interactive demos and open discussions to help gain insight from the experiences of the participants. Over the seven user sessions (see Table 4-1), stroke participants were trained on the system and gave their ratings for motivation in alarm vs. continuous vs. music conditions. Most participants were able to choose a favourite song in advance to move along to self-selected favourite music. Each participant was timetabled to receive individualised therapy time for 30 minutes per session. Detailed reflexive notes were taken after each session to document and inform the research considerations in an iterative process.

Movement tasks

Participants completed up to five blocks of movements lasting, on average, 2 minutes per block. Each block consisted of a movement task paired with sound or silence. The movement tasks were recommended by staff and were relevant to the participants' level of impairment. All tasks involved forward reach, aiming towards function where possible (e.g. reaching for a computer mouse). At the end of each bloc, the participants were asked questions about their experience. Participant 5 did not show any interest in music, and therefore, did not do any movements with music but still trialled the system with the staff and gave feedback on the use of de-weighting. Participant 10 did not have time to take part after a technical issue with the system setup but similarly gave constructive feedback on the core research ideas.

Participant feasibility questionnaire

A tailored questionnaire was developed in collaboration with the research team, including the PhD candidate, supervisors, and on-site neurologist, to assess the usability, acceptability, and experiential aspects of using the novel system. Five-stage Likert scales, yes/no answers and more open-ended questions were administered orally for participants to quickly give feedback on their perceived levels of enjoyment, tiredness, and auditory changes. Two questions were informed by the Intrinsic Motivation Inventory (IMI) (McAuley et al., 1989); specifically, the effort and interest/enjoyment subscales from the IMI were drawn on to assess patient enjoyment levels while performing the tasks. While not a validated questionnaire, this mixed methods approach aimed to gain initial feasibility insights on patient experiences using the novel auditory feedback system to guide the system design and research protocol. The development process involved input from clinical and academic experts to ensure questionnaire relevance.

Participants in the first six sessions answered the following questions after every block:

Q1: How tired do you feel now?
(1) Not at all (2) A little tired (3) Quite Tired (4) Very Tired (5) Extremely Tired
Q2: How much did you enjoy playing?
(*1) Not at all (2) It was ok (3) it was enjoyable (4) I really enjoyed it (5) Loved it*
Q3: Did you notice any change to the music/sound? [yes/no]

- yes: Did you adjust your movement based on the change you heard?

Immediately after completing the sessions, participants then answered the following three questions:

Q4: What type of feedback did you prefer?
Q5: What type of feedback did you think was most useful and why?
Q6: Any other comments

Table 4-1: *Case studies: data, session number, task, session duration, number of participants and staff, impairment levels of participants*

date	session	task	duration	pts	staff	mild (n=2)	moderate (n=3)	severe (n=4)
01-Aug-18	1	Reach for a computer mouse	1 hour	2	1			(P1, P2)
10-Aug-18	2	Sliding a computer mouse	1 hour	2	1			(P1, P2)
21-Sep-18	3	Sliding arm on a table	1 hour	2	1		(P3, P4)	
26-Sep-18	4	Reach and press telephone	1 hour	2	1		(P3, P4)	
25-Oct-18	5	Reach for a jar	1 hour	2	4	P6		P5
31-Oct-18	6	Reach for a target button	1 hour	2	1	P6		P7
05-Dec-18	7	Reach for a target button	1.5 hours	3	2	P8	P9	

Note: 10 participants are listed as P1-P10. P1-P4 and P6 attended two sessions each, while the remaining participants attended one session. Each participant was seen with a staff member and the researcher separately for up to half-hour sessions as part of feasibility for the NHS study protocol. There was a range of impairment (mild, moderate or severe).

Feedback Trials

During the seven sessions, a total of 53 trials were carried out, encompassing the exploration of 10 different sound and auditory feedback variations, as summarised in Table 4-2. These variations included different types of self-selected music with various real-time effects applied, as well as trials involving silence and percussion samples. In these trials, three distinct compensation types were assessed: shoulder abduction, trunk flexion, and shoulder elevation. Notably, shoulder abduction emerged as the most commonly addressed compensation movement.

Table 4-2 provides an overview of the case studies, including the sound type, auditory feedback, total trials, total unique participants, and the distribution of compensation types (shoulder abduction, trunk flexion, and shoulder elevation). The iterative research process focused on conducting more trials of exercises that demonstrated utility in the research, allowing for a comprehensive evaluation of the ten distinct feedback varieties. It is important to note that not all participants participated in all conditions, and two participants did not complete any exercises. However, they actively engaged in discussions about the research, providing valuable insights into the ideas and methodologies employed.

Table 4-2: *Case studies: variation, sound type, auditory feedback, total trials, total participants, compensation type totals*

Variation	Sound Type	Auditory Feedback	Total Trials	Total Pts	SA	TF	SE
1	SS music	None	6	6	6	4	4
2	SS music	Distortion	17	6	6	6	2
3	SS music	Pitch Down	8	4	4	3	1
4	SS music	Tempo Speed Up	5	4	4	2	0
5	SS music	Tempo Slow Down	4	3	3	3	1
6	SS music	Mute/Silence	2	2	2	2	2
7	SS music	Alarms	4	2	6	1	0
8	None (silence)	Alarms	2	2	2	2	2
9	None (silence)	None	4	4	4	4	4
10	Samples (Kick & Snare)	None	1	1	1	0	0
total	10	10	53	8	38	27	16

Note: SS = self-selected. Total Pts are the unique participants who did at least one of the exercises as listed by sound type and feedback type. SA = shoulder abduction, TF = trunk flexion, SE = shoulder elevation. Ten exercises were trialled at least once with an iterative process focusing on doing more of the exercises that were found to be most useful in the research. The three compensatory types list the total number of times an exercise was trialled per sound condition. No condition was mutually exclusive; for example, not all participants took part in all conditions, and two participants did not complete any exercises, hence there being eight in the total row with P5 and P10 not doing any of the music exercises. They did both, however, talk about the research and provide insight into the ideas.

4.3.4 Analysis

The analysis of the study data employed a mixed-methods approach, integrating both quantitative and qualitative methods to explore the feasibility and acceptability of the auditory feedback approach for neurorehabilitation. This analysis considered the concurrent workshops running in parallel, which could have had an impact on participant experiences and perceptions. Quantitative data from self-report questionnaires were analysed were possible using descriptive statistics. Means and standard deviations were calculated for item ratings related to perceived tiredness and enjoyment. The presentation of average ratings on these questionnaire measures served as a complementary component to the qualitative insights. This quantitative analysis enabled a broader understanding of the participants' collective responses. Open-ended questions provided participants with the opportunity to express any experiences or opinions regarding the auditory feedback approach. Participant quotations and statements were incorporated to illustrate and support while also considering any interplay with the parallel workshops described in Chapter 3. The reflexive notes were analysed using thematic analysis to identify patterns and key findings. Staff and service user feedback and recommendations for system design improvements were analysed while addressing technical challenges that emerged during the sessions and workshops running in parallel.

4.4 Results

4.4.1 Participant feasibility questionnaires

The results from the feasibility questions on perceived tiredness, enjoyment and auditory feedback are displayed below (see Table 4-3). Average enjoyment ratings for self-selected music were rated as 3.4 ("it was enjoyable") compared to 1.67 in silence ("it was ok"). Coupled sound conditions, which included the use of auditory filters such as distortion that were layered over self-selected music, were at times ambiguous, as indicated by participants not noticing feedback or alternatively noticing feedback but not being able to reduce their compensation successfully.

During some of the early sessions, participants were permitted to use active (A) and active assisted (AA) movements where they used their non-affected arm to aid their affected arm in undertaking forward-reaching tasks. It was interesting to note that participants tended to rate their enjoyment higher in the AA condition, but this condition was also found to trigger minimal feedback due to the participant moving with little compensation. Staff stated that they would encourage active movement where possible, and this aligned with aiming to make the

Table 4-3: *Participant Questionnaire: auditory feedback perception, average ratings of enjoyment and tiredness*

Variation	Sound Type	Auditory Feedback	Noticed Feedback Total pts	Did not Notice Total pts	Altered Movement Total pts	Not Altered Total pts	Tiredness M	Tiredness M
1	SS music	None	NA	NA	NA	NA	3.40	2.13
2	SS music	Distortion	8	6	6	3	3.41	2.25
3	SS music	Pitch Down	7	0	3	4	3.00	3.13
4	SS music	Tempo Up	4	0	2	2	2.25	3.50
5	SS music	Tempo Down	3	0	1	2	4.00	1.75
6	SS music	Mute/Silence	2	2	2	NA	NA	3.50
7	SS music	Alarms	2	0	2	2	3.00	3.67
8	None (silence)	Alarms	2	NA	2	NA	NA	3.00
9	None (silence)	None	NA	NA	NA	NA	1.67	2.67

Note: SS = self-selected; M = mean ratings based on the Likert questions; NA = not answered or not applicable. Only 9 variations are listed as number 10 with samples was trialled once and the participant verbally disliked this, and it was dropped as a condition to focus on the other exercises.

task challenging enough to receive auditory feedback. Table 4-4 below shows this difference in ratings between A and AA conditions. Furthermore, participants rated their tiredness as higher in the majority of cases in the active conditions. Some participants with mild impairment did not find active conditions very effortful, reducing the difference perceived between A and AA conditions.

Qualitative responses to the final three feasibility questions addressing feedback preferences, perceived ability to make use of the feedback and other comments are summarised below (see Appendix 4-1 for individual responses). The findings derived from the participant questionnaire provided valuable insights into the nuanced participant preferences and perceptions concerning the auditory feedback approach. Six broad themes arose summarised below:

Table 4-4: *Participant Questionnaire: auditory feedback, average ratings of enjoyment and tiredness*

Variation	Sound Type	Auditory Feedback	Enjoyment AA	Enjoyment A	Tiredness AA	Tiredness A
1	SS music	None	4.00	3.00	2.50	2.00
2	SS music	Distortion	4.00	3.48	3.00	2.20
3	SS music	Pitch Down	2.00	3.43	2.00	3.00
4	SS music	Tempo Up	NA	2.25	NA	3.50
5	SS music	Tempo Down	NA	4.00	NA	1.75
6	SS music	Mute/Silence	NA	NA	NA	3.50
7	SS music	Alarms	4.00	2.50	2.00	4.50
8	None (silence)	Alarms	NA	NA	NA	3.00
9	None (silence)	None	NA	1.50	NA	2.50

Note: SS = self-selected; NA = not answered or not applicable; A = active; AA = active assisted. All variables are mean ratings from the Likert scale questionnaire Q1: How tired do you feel now? And Q2: How much did you enjoy playing?

Theme 1: Preference for Auditory Feedback Types

Participants displayed a range of preferences for auditory feedback types, highlighting the individualised nature of their experiences. For instance, Participant 1 expressed a clear preference for continuous coupled sound feedback over alarms, deeming the latter as not engaging, stating: *"It's just not motivating."* Participant 6 favoured "Distortion," suggesting that certain feedback types resonated more with specific individuals. Additionally, participants showed a preference for self-selected music, which seemed to impact their motivation significantly. For example, when participants were allowed to use their chosen music during exercises, it was evident that their motivation increased. This preference for self-selected music enhanced their overall engagement and enthusiasm during rehabilitation sessions.

Theme 2: Perceived Usefulness of Feedback

Participants were able to make use of feedback and could perceive the use of it, as evidenced by Participant 4 stating: "I'm aware of the movement. Keep my elbow in a little bit more." However, there was no consensus on which type of feedback was perceived to be most useful. Participant 3 found value in pitch bend-down feedback, citing its clarity and ease of auditory perception. In contrast, Participant 6 described layered distortion as immediate and assertive, underlining its effectiveness in delivering feedback. However, during these sessions with service users and the workshops (see Chapter 3), concerns were raised regarding the potential ambiguity of layered sounds, which should be carefully considered. Silence in ongoing music emerged as a distinct form of feedback that participants found most salient for enhancing their movements. Several participants, such as Participant 9, highlighted the usefulness of silencing the music. They emphasised that periods of silence allowed them to concentrate on their movements and make necessary corrections. Participants and therapists highlighted the need for clarity in auditory feedback, recognising that layered or complex sounds might introduce confusion or challenges in interpretation. This observation underscores the importance of designing auditory feedback systems that maintain clarity and avoid potential ambiguity, ensuring participants can effectively utilise the feedback to improve their movements.

Theme 3: Motivation and Enjoyment

Participants emphasised the motivation they experienced from their use of the system. As one participant stated, "Anything that can make it more fun. Repetition is monotonous… the repetition becomes more fun." This sentiment was further accentuated by a participant who likened the auditory feedback approach to "having a physio here saying you are not doing it right.", underlining the motivational aspect of the feedback as it mimics the presence of a supportive therapist.

Theme 4: Challenges and Concerns

Participants articulated challenges and concerns regarding the auditory feedback approach. One participant expressed that hearing was an issue, highlighting the critical role of auditory perception in the effectiveness of this feedback method. This acknowledgement underscores the need for personalised solutions, such as individualised volume adjustments or alternative feedback modalities, to cater to participants' unique hearing abilities. Additionally, challenges related to specific movements were raised, with a participant mentioning difficulties in "stretching my elbow." This remark underscores the necessity of customising auditory feedback to accommodate varying levels of motor skill proficiency and physical limitations.

Theme 5: Interest in Music and its Impact

Participants demonstrated a strong interest in using music during rehabilitation exercises. They found that music significantly boosted their motivation, encouraging them to engage more effectively in the exercises. Additionally, participants appreciated how music could trigger memories, adding a meaningful and emotional dimension to their rehabilitation experience. One participant stated, "Music will bring back some of our earliest memories."

Theme 6: Future Potential

Participants displayed optimism regarding the future potential of the auditory feedback approach. They believed it could be extended to a broader range of exercises and anticipated its continued utility in neurorehabilitation. One participant expressed, "I think it's a very good idea," while another stated, "They will do more exercises – I think it will really work." Another participant commented, "Training in the home and learning on your own - this would be good." This observation highlights the potential for extending auditory feedback to home-based rehabilitation programs, allowing individuals to take a more proactive role in their rehabilitation.

4.4.2 Defining auditory feedback

Auditory feedback variations were iterated over the sessions. The conditions were actively monitored and removed based on direct feedback from participants and observations on success and failure during the sessions. By session six, all feedback types were dropped except for distortion due to the ambiguity of the feedback types, as participants found it challenging to make use of the auditory feedback to reduce their compensatory movements.

By the final session, distortion was also dropped from the auditory feedback variations and the binary auditory feedback variations using either self-selected music with silence to signal compensation (variation 6) or self-selected music with alarms (variation 7) to signify compensation.

4.4.3 De-weighting feasibility session

One of the OTs stated that it would be beneficial to include participants who had weaker active function of the arm but who could undertake the exercises if gravity was reduced. The SaeboMAS and SaeboMAS mini are versatile mobile arm support devices designed to assist individuals with shoulder instability and weakened arms, promoting increased motor control, strength, and range of motion in a zero-gravity setting. These devices offer adjustable tension levels and height providing, freedom of movement in any direction[4]. Hence, in one of the user sessions, P5, who did not have enough active strength to do the exercises without support, tested using a mini mobile SaeboMAS arm support that clamps to a table and reduces gravity. This support was found to work in both permitting the user to undertake the forward-reaching tasks and did not interfere with the participants' arm being tracked by the system. A larger SaeboMAS was also used, but this was hard to set up in the room; consequently, it was decided that the smaller table clamp SaeboMAS would be the most suitable out of the two arm supports. However, after successful trials using slide sheets[5] to remove gravity, this was deemed a suitable option permitting the recruitment of participants with severe impairment, such as P1 and P2. Furthermore, using a slide sheet could transfer into the home environment more easily than the arm supports and still help remove gravity effectively.

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[4] The SaeboMAS range is available encouraging zero-gravity https://www.saebo.com/shop/saebomas/

[5] Sheets of paper and plastic gliding sheets were used to permit smoother movements across the tabletop.

4.4.4 Defining the task and study blocks

Setting the maximum reach suitable to the participant was important, and the staff helped to define this based on their clinical reasoning, working to each participants' current ability and level of impairment. The tasks were progressively reduced in complexity over the sessions, with the final task being an active forward reach to a target button, which was deemed relevant to participants in all impairment groups. Staff recommended that participants take short rests after each block with ten repetitions per block being suitable for most participants. Longer blocks of up to 2 minutes were frequently too challenging for participants. Over the sessions, staff helped refine the tasks trialled with participants, ensuring that severe, moderate and mild impairment levels could be included in the study. Performing an active forward reach in a neutral position was found to be a highly relevant task to all participants.

4.4.5 Defining compensation for real-time feedback

Ten different sound combinations were trialled. Self-selected music with silence as the auditory feedback was rated as the easiest to make use of by the participants who tried this condition. Moreover, self-selected music was rated the most enjoyable compared to other conditions such as silence. Based on the consultation workshops and ongoing participant sessions, it was decided that the three compensation feedback types (shoulder abduction, trunk flexion and shoulder elevation) should be combined into one single number variable using appropriate logic in Pure Data. Whichever compensation had the highest current error threshold took priority and was sent through to trigger the compensation feedback; this meant participants were required to problem-solve their way out of compensation. Participants were not explicitly told what type of compensation was occurring. However, based on the user sessions and consultation sessions (documented in Chapter 3), it was clear that participants required explicit instructions on the study conditions to whether to expect feedback.

4.4.6 Post session questions & reflexive session notes

Technical and practical insights emerged during the user sessions. They were documented in the reflective notes taken by the researcher after each feasibility session (see Appendix 4-2 for expanded summary and notes). Five key recurring themes across the seven sessions are summarised below:

Theme 1: Session Effectiveness and Technical Challenges

The initial sessions underscored the need for improved system effectiveness, especially for participants with weak arm function. Technical issues with rep tracking, block tracking, and other aspects were identified, signalling the necessity for system refinements and more automated functionality. Challenges related to pose recognition, potentially influenced by factors like lighting and attire, were acknowledged, emphasising the importance of robust tracking mechanisms. Participants' feedback suggested the potential utility of incorporating alarms in addition to music-based feedback.

Theme 2: Participant Awareness of Auditory Feedback

Participant responses indicated varying degrees of awareness regarding auditory feedback. While some participants readily noticed auditory feedback, others exhibited difficulties due to limited active movement capabilities. The possible impact of the participants' perceived effort on their ability to discern and respond to auditory changes was highlighted. It was evident that the clarity and saliency of auditory feedback played a crucial role in participants' ability to notice changes.

Theme 3: Effective Utilisation of Feedback and Preferences

Participants' capacity to utilise auditory feedback to modify their movements was explored. It became apparent that effectiveness varied among participants, often influenced by their hearing capabilities and the clarity of feedback. The preference for specific types of feedback emerged, with some participants expressing a preference for distortion over other modalities. Notably, one participant deemed the pitch change the most useful. This raised questions about the relationship between pitch and movement error and its potential relevance in enhancing participant engagement.

Theme 4: Optimal Number of Movements and Rest Periods

The sessions provided insights into determining the optimal number of movements and rest periods tailored to individual participant needs. Factors such as fatigue, cramping, and effort exerted during tasks played a significant role in the design of training parameters. It was observed that shorter blocks and more frequent rests were suitable for severely impaired participants, while those with fewer impairments could manage two-minute blocks with intermittent rests.

Theme 5: Technical Refinements and System Setup

Technical refinements were identified as essential components of the system's development. Calibration issues that led to extreme sound changes were addressed through model precision adjustments and optimised smoothing techniques. The importance of accurately mapping movement data to sound filters was highlighted, with suggestions to improve the scaling of filters and address timbral differences during activation. A proposal to integrate sensor fusion, possibly involving an accelerometer on the wrist, was discussed to enhance data capture during active sessions.

These reflective session notes provided valuable insights into the iterative development of the auditory feedback system, helping shape its design to meet the specific needs of individuals with chronic stroke. These sessions ran in parallel with ongoing workshops, fostering a collaborative approach that enhanced the research process. An example of more detailed reflexive notes is given in Appendix 4-2 for the first participant session, describing the session overview as follows: 1) task, 2) conditions, 3) kinematic data collection, 4) training of the system, and 5) the system setup. This is to illustrate the iterative nature of the technical development employed throughout the development and feasibility testing process.

4.4.7 Machine learning models and calibration

Machine learning models were trained to evaluate forward reach movements. Three separate models were trained to represent each type of compensation (see Figure 4-3 showing inputs and outputs). The models permitted the system to determine whether any compensatory movements occurred above a threshold that was set by therapists. The threshold was a value between 0 (the lower bound of the model when a participant was moving with optimal movements) and 1 (the upper bound of the model representing the maximum compensatory moment). A threshold of around 20% (~0.2) was found to be most effective to give relevant feedback and reduce interference of noise in the system. Compensatory movement above this threshold resulted in auditory feedback, as noted in the sound trials listed in the tables above. Two further models were recorded to give the start position of the target movement and the endpoint (target position), which were used to track the total number of repetitions that a participant achieved by counting the number of targets reached. Linear regression models were far quicker to train with participants and staff than NN models and were found to be more efficient in providing feedback to participants. NN models were found to fluctuate more, and that inherent noise in the system made the feedback more erratic and harder for participants to utilise. All data was time-stamped every 20 milliseconds and allowed the dependent variable (DV) to be calculated. The DV was a compensation percentage score (i.e., the amount of time spent using compensatory movement). Percentage compensation scores could be calculated for each repetition of the target movement and then averaged across blocks for analysis.

Training and Calibration with Therapist Validation

In the Sonic Sleeve system, a structured training and calibration phase was employed to ensure the system's accuracy and personalisation to each participant. Therapists had a crucial role in validating and fine-tuning the system. The process involved seven key steps:

(1) Baseline Setup: Participants perform five repetitions of their optimum movement, establishing a baseline for the system's compensatory models.
(2) Shoulder Abduction: Participants set the maximum threshold for shoulder abduction by holding their elbow 15 cm from their body.
(3) Trunk flexion: Maximum trunk flexion is determined as participants lean forward 10 cm from the back of the chair.
(4) Shoulder Elevation: Maximum shoulder elevation is set by lifting the shoulder by 5 cm.
(5) Start Pose: The start position of the target movement is recorded.
(6) Target Pose: Participants define the target pose by touching the end target (e.g. computer mouse)
(7) Calibration: A brief calibration test ensures that all models accurately track compensatory movements and poses.

Therapists validate the thresholds for compensatory movements, providing expert input to align feedback with where, in their professional opinion, a service user should be in their rehabilitation trajectory. The data for any of the training models could be deleted and retrained if data quality was suboptimal or therapists decided there was a more optimal movement pattern for the participant to move. This structured process personalised the Sonic Sleeve system, making it highly effective in providing real-time feedback during rehabilitation exercises. The integration of therapist validation ensured that the system's thresholds and models were in alignment with their clinical reasoning and could be fine-tuned to each user's unique needs and capabilities.

4.4.8 Description of the completed system

The Sonic Sleeve system was developed through an iterative process and completed by the end of the last participant facing session (see Figure 4-2). See section 4.3.3 for a more detailed description of the motion capture system. An MSI laptop running Ubuntu 16.04 formed the base computing hardware with a Logitech webcam used for motion tracking. The webcam captured participant movements and fed this video data into the OpenPose software (Cao et al., 2017; Wei et al., 2016) to extract key joint coordinates mapped to upper limb movements. This time series kinematic data was input into the Wekinator machine learning platform (Fiebrink et al., 2011) to classify compensatory movements in real-time.

Auditory feedback was provided to users through speakers using Pure Data (see Figure 4-1), an open-source visual programming language designed for multimedia applications. Pure Data took the output predictions from Wekinator and used pre-defined mappings to manipulate properties of the user's self-selected music playback when compensation thresholds set by therapists were exceeded. In this way, *Sonic Sleeve* provided real-time feedback on movement quality through continuous auditory information to optimise reaching tasks. A diagram showing the entire system with user interaction and automated processes is depicted in Figure 4-3.

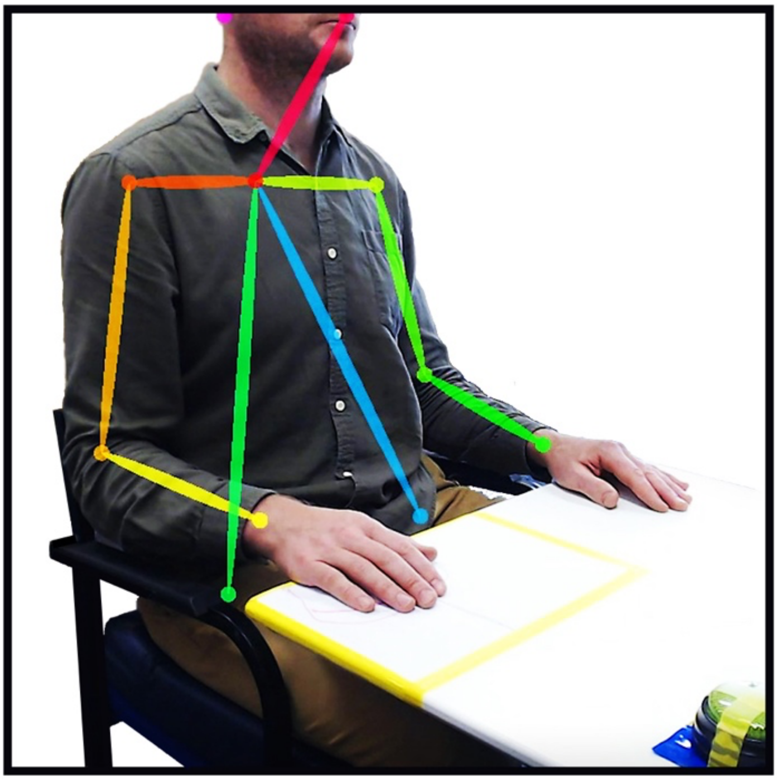

Figure 4-2: 2D position data output from OpenPose via a webcam tracking joint positions. The dots represent the 2D position of each joint, and the lines represent the relationships between joints. The exact colouring is not standardised and can vary with the overall purpose of helping visually segment the pose estimation results.

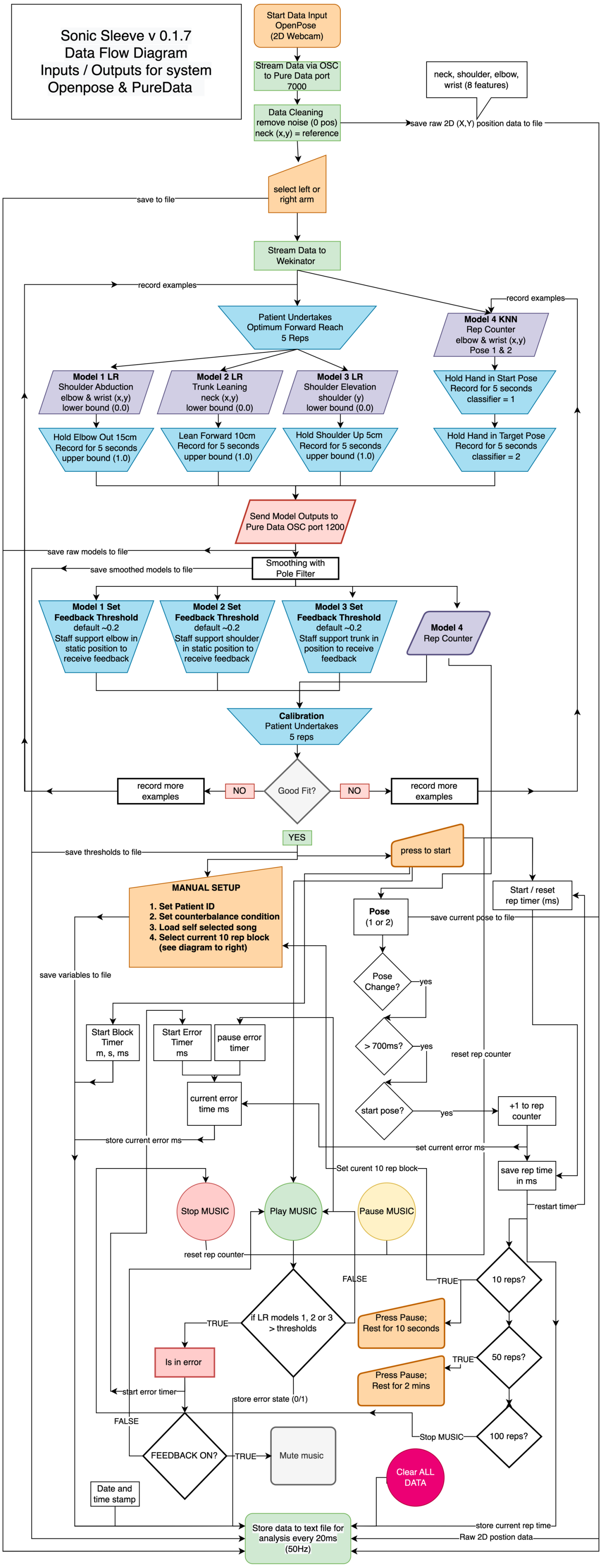

Figure 4-3: Inputs and outputs for the Sonic Sleeve auditory feedback system. A webcam provides the video input to track user movements using pose estimation. This skeletal tracking data is input into machine learning models that classify compensation levels. The output predictions control the music playback properties to deliver real-time auditory feedback on movement quality.

4.5 Discussion

Over the seven user sessions with ten participants with chronic stroke, several critical decisions were made regarding the use of sound and the technical implementation of the system. A broad understanding of how the QSUL programme was run due to the consultation workshops described in Chapter 3 helped to embed the research directly in the QSUL service. Measuring compensatory movements using individualised machine learning was found to be the most useful way to provide real-time feedback to support optimal movements. The final dependent variable for analyses became the proportion of time participants spend in compensatory movements.

As evidenced in the sessions working directly with participants, many of the auditory feedback trials were ambiguous, with the continuous mapping of sound onto filters hard to perceive for many of the participants and staff that trialled the various conditions. Coupled sounds made compensation reduction more challenging to be aware of and not effective enough to reduce compensation successfully. Therefore, a more straightforward auditory mapping within a motivational framework was decided upon using self-selected favourite music and muting of the music as a simple salient signal to give auditory feedback to participants as soon as they began to compensate. The optimum movement could be enhanced with auditory feedback signalling to the participant as soon as compensation was tracked in the system. The two discrete feedback types, alarms or muting of music, were more salient than the other feedback modalities. However, alarms were perceived as “annoying”, and muting of music was preferred by participants and used for the final NHS research protocol.

There are some noted limitations to the *Sonic Sleeve* system, particularly regarding its use of 2D camera tracking and the validation process involving therapists. The adoption of 2D cameras for tracking offers practical advantages, such as cost-effectiveness and accessibility. However, these benefits come with potential challenges related to tracking accuracy, primarily due to occlusion, where body parts may temporarily obstruct each other from the camera's view, leading to tracking inaccuracies. Additionally, the need for specific hardware placement, as highlighted by Webster & Celik (2014), can limit system flexibility and require precise setup for optimal performance. Moreover, the validation process, which relies on therapists’expertise, introduces subjectivity into the evaluation. Therapists’varying judgments may affect the system's overall consistency and reliability. Balancing these advantages and limitations is essential when assessing the *Sonic Sleeve* system's effectiveness, and ongoing research and technological advancements may help mitigate these challenges.

As the study was running on the stoke unit where participants were receiving such a high dose of rehabilitation the outcome measure needed to be highly targeted and be attained within the session. As a proof of concept, the research would focus initially on a simple impairment movement and active forward reach was agreed to be the most appropriate.

4.6 Conclusion

Running the series of 10 case studies helped to design a new upper limb rehabilitation system to track movement quality in real-time. The direct user feedback from participants with chronic stroke and staff gave a solid clinical and scientific rationale for the research to move forward and test the system using auditory feedback in a larger cohort of participants.

CHAPTER 5: WITHIN SESSION COMPENSATORY MOVEMENT REDUCTION USING AUDITORY FEEDBACK

5.1 Introduction

Based on the conclusions drawn from the workshops with medical staff and seven sessions with participants with chronic stroke detailed in the previous chapters, several experimental studies were undertaken. The studies assessed a digital approach for identifying and signalling compensatory movements in real-time so that participants could use the information to make postural corrections. The emphasis on self-correction is important: while in a clinical setting, physical harnesses are often used to prevent compensatory movement (Michaelsen et al., 2006). However, such an approach does not easily translate to the wider context of home-based rehabilitation, where an awareness of one's posture and the ability to self-correct is challenging without a therapist. Recent developments around digital technology for rehabilitation have encompassed a range of approaches such as wearable systems (Wang et al., 2017a) biofeedback systems (Yungher & Craelius, 2012) and robotics (Huang & Krakauer, 2009). Surprisingly, these approaches have rarely been used to help correct compensatory movement patterns, and those that have (Benavides & Adolfo, 2017; Valdés et al., 2017) are only suitable for large-scale clinical environments due to considerable cost and space requirements.

In contrast, the approach developed and tested in this thesis was designed to be low-cost, low-resource and consequently suitable for the home environment. The system developed - *Sonic Sleeve* - uses computer vision and machine learning (ML) algorithms to detect and signal to the participant when compensatory movements are occurring. Participants listen to self-selected favourite music while making repetitive target movements. If a repetition includes compensatory movement (predefined through a calibration phase), the music is muted and resumes only when this is corrected. In a clinical setting, guidance about how to correct would be suggested by a therapist. In contrast, *Sonic Sleeve* requires participants to notice the muting of the music and to determine which postural modification is required, as would be the case in the home environment, where a therapist is not present. Together, the approach combines a motivating and rewarding context for repetitive movement, while incorporating embedded feedback to guide optimal patterns of movement. As covered in Chapter 2, Knowledge of Results (KR) provides feedback regarding the overall success or failure of a motor task, while Knowledge of Performance (KP) gives real-time insight into qualitative execution (Schmidt & Lee, 2019). The auditory feedback in the current studies functioned primarily as a form of concurrent KP by informing participants in real-time when compensatory movements exceeded predetermined thresholds during task execution.

This chapter describes two experimental studies (1A and 1B) which addressed the overarching research question: Can participants with chronic stroke perceive and make use of auditory feedback (muting within self-selected music) to reduce compensatory movements in a seated active forward-reaching task? And the secondary question: Are there differences in clinical baseline characteristics between participants who show larger versus smaller reductions in compensatory movements with auditory feedback? Experiment 1A reports on data collected in a clinical lab setting while Experiment 1B reports on feasibility data collected in the home environments of participants with chronic stroke.

5.2 Experiment 1A: Sonic Sleeve in the Lab

5.2.1. Aims

The primary aim of Experiment 1A was to assess whether real-time auditory feedback, provided through muting of music, could reduce the duration of compensatory movements in an active reaching task compared to a condition without feedback in a controlled environment. The secondary aim was to explore the relationship between response to feedback and the clinical baseline measures, both by comparing the highest versus lowest responders, and by investigating potential correlations between improvements with feedback and the clinical baseline scores.

5.2.2 Materials and Methods

5.2.2.1 Study Design

A within-session, within-subject design with two conditions (with feedback vs. without feedback) presented in a randomised counterbalanced order was used. Participants were assigned to their starting condition using a random number generator (https://www.randomizer.org/#randomize) and based on their study ID number. Given the limited number of potential eligible participants and intensive nature of the rehabilitation program, a within-session, within-subject design was best suited to efficiently maximise data collection while controlling for confounds. Conducting the study within a single session for each participant minimised external variability from other ongoing therapy activities and individual differences, while counterbalancing the conditions controlled for practice effects. This within-subject approach also provided more statistical power with a smaller sample size. Overall, the design helped isolate the effects of auditory feedback on compensatory movements within a busy therapy schedule while avoiding carryover effects between conditions.

5.2.2.2 Participants

All participants taking part in the study were enrolled on the Queen Square Upper Limb (QSUL) neurorehabilitation programme (Kelly et al., 2020; Ward et al., 2019) at the National Hospital for Neurology and Neurosurgery. None of the participants that took part were from previous research described in Chapter 4. As detailed in Chapter 2 the QSUL neurorehabilitation programme is intensive, delivering 90 hours of therapy over a three-week period. Twenty-five participants were screened (see Figure 5-1) with 23 fulfilling the eligibility criteria as follows: (1) diagnosis of stroke resulting in hemiparesis at least 6 months prior to study; (2) ability to give informed consent; (3) ability to follow three-stage commands; (4) ability to lift the affected hand onto a table whilst seated but unaided by their unaffected limb; (5) ability to sit unsupported for at least 10 minutes; (6) aged between18-75; (7) at least minimal ability to actively extend their elbow. Two participants were excluded as one had no active elbow extension and the other was non-stroke. Two participants dropped out: one due to a family bereavement and the other due to high levels of fatigue. Data for one participant was not collected due to a software failure leaving 20 participants with full datasets. Table 5-1 shows participant details, including scores on a range of clinical measures that are routinely assessed. Restricting the age of participants to below 75 was set to help control for confounding variables, reduce safety concerns and enhance recruitment feasibility. Written informed consent was given by all participants (see Appendix 5-2) and full ethical approval was attained by the London Dulwich research ethics committee (ref: REC 19/LO/0579 see Appendix 5-3). Additional ethical clearance was obtained from Goldsmiths University (see Appendix 5-4).

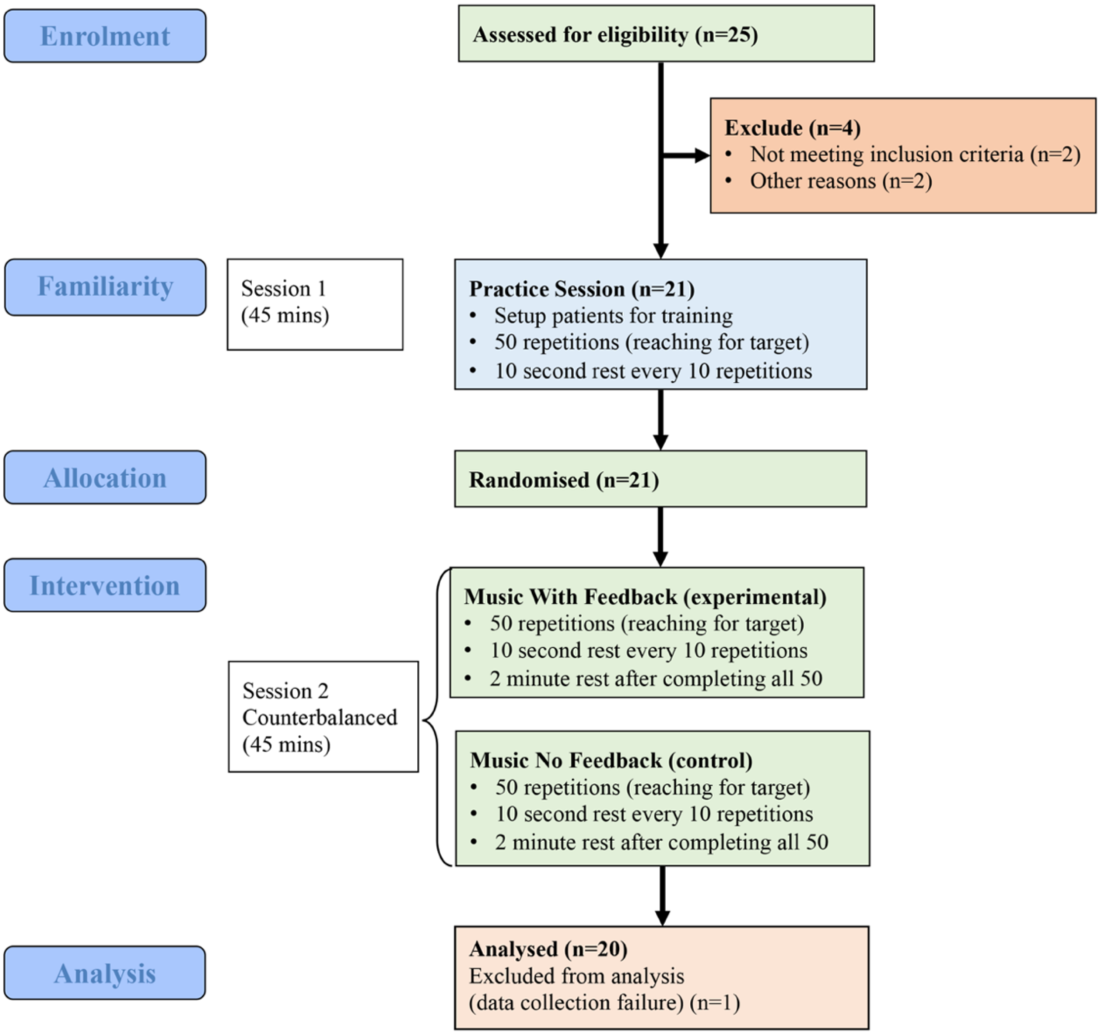

Figure 5-1: Flow diagram for Experiment 1A

Participant Recruitment

Potential participants were identified and approached by the medical team at the QSUL neurorehabilitation programme. Participants enrolled in the intensive rehabilitation program who met the initial eligibility criteria were informed about the study by their treating therapists. Interested participants were then provided with a printed participant information sheet (PIS) detailing the study aims, procedures, risks and benefits. They were given time to read over the information sheet and ask any questions to the researcher. If they agreed to take part, participants signed a written informed consent form approved by the ethics committee. This outlined what participation would involve, confidentiality practices, and their right to withdraw. Participants were provided with a copy of the consent form to keep. Following informed consent, an additional screening process was conducted by the researcher and medical team to confirm eligibility based on the full eligibility criteria.

5.2.2.3 Description of the Lab-Based Sonic Sleeve System

The *Sonic Sleeve* system for Experiment 1A takes kinematic movement data from a 2D webcam using the open-source software OpenPose (Cao et al., 2017; Papandreou et al., 2018) and maps that data to provide real-time auditory feedback to the participant. The framerate of data collected via OpenPose was between 10-30 fps. For relatively slow-paced rehabilitation exercises like active forward-reaching tasks, as used in this study, 10 fps provides adequate sampling of the movement trajectories capturing compensatory movements reliably from durations as short fas 100ms. The interactive machine learning platform Wekinator (Fiebrink et al., 2011) was used to record the 2D position data from the participants' neck, wrist, elbow and shoulder. In the present set of experiments, the auditory feedback was a simple binary signal: the music was either on or off (muted) according to whether the system detected compensatory movements during an active forward-reaching task.

Table 5-1: *Demographic and clinical characteristics of 20 participants for Experiment 1A*

Patient ID (n=20)	Gender (M=75%)	Age* (years)	AL (R=85%)	DH (R=75%)	TSS* (months)	mRS* Max=5	BI* Max=20	NFI* Max=62	HADS* Max=34	MoCA* Max=30	FMS* Max=12	FM-UL* Max=54	ARAT* Max=57	CAHAI* Max=91	Arm-A* Max=28	Arm-B* Max=52	Apraxia* (Yes=15%)
1	M	62	R	L	32	3	18	52	12	na	12	13	16	20	9	31	Yes
2	M	63	R	L	23	3	20	39	17	25	12	28	25	36	16	47	No
3	M	64	R	R	62	3	17	46	9	23	12	15	23	27	7	41	No
4	F	47	R	R	13	2	18	39	9	28	12	14	20	29	6	38	No
5	M	55	R	R	137	2	19	34	8	25	12	18	17	44	2	48	No
6	M	61	R	R	8	3	16	38	23	29	11	40	35	55	3	33	No
7	F	51	L	R	18	3	17	41	22	30	7	24	52	64	4	14	No
8	M	49	R	L	23	3	17	39	12	19	11	38	28	37	0	19	No
9	M	36	R	R	30	2	20	na	12	26	12	20	18	32	11	36	No
10	M	64	R	L	23	3	20	23	1	na	10	32	14	28	5	25	Yes
11	M	50	R	R	14	3	19	46	18	30	10	29	29	52	3	46	No
12	F	27	L	R	108	3	20	59	27	25	11	13	14	26	15	45	No
13	F	39	R	L	23	3	18	43	12	26	10	33	40	64	1	21	No
14	F	19	R	R	17	3	16	na	na	na	10	17	22	46	1	43	Yes
15	M	58	R	R	28	3	18	38	5	16	10	33	35	60	6	26	No
16	M	54	R	R	43	3	19	39	13	30	6	23	20	53	8	43	No
17	M	51	R	R	23	2	18	42	12	na	8	44	37	43	2	39	No
18	M	72	R	R	26	2	19	41	2	29	12	22	20	35	8	42	No
19	M	68	R	R	18	3	17	26	1	14	12	28	42	57	0	19	No
20	M	63	L	R	16	3	16	27	17	28	8	14	10	32	9	30	No
Mean(SD)		53(14)			34(33)	3(0)	18(1)	40(9)	6(4)	25(5)	10(2)	25(10)	26(11)	42(14)	6(5)	34(11)	

Table 5-1 Abbreviations: AL = affected limb; DH = dominant hand; TSS = time since stroke; mRS = modified Rankin Scale; BI = Barthel Index; NFI = Neurological Fatigue Index; HADS = Hospital Anxiety and Depression Scale; MoCA = Montreal Cognitive Assessment

Setting lower and upper bounds for each participant

Examples of compensatory movements were recorded into separate ML models, comprising: i) shoulder abduction ii) shoulder elevation iii) trunk flexion. Each participant held static positions for five seconds at a time as follows: shoulder abduction by holding the elbow out by ~15cm; trunk flexion by leaning forward ~10cm from the back of the chair; and shoulder elevation by raising the shoulder by ~5cm. These compensatory positions set the maximum upper bounds of the three ML models at 1.0, whereas the lower bounds were set to a value of 0.0 by recording five examples of the target movement performed using the most optimal movement pattern possible. Both the compensatory (upper bound) positions and the optimal movements (lower bounds) were physically supported by an occupational therapist (OT) or physiotherapist (PT) when required, ensuring the participants did not become fatigued and to help ensure the upper and lower bounds of the system were set at consistent levels. For example, some participants while undertaking their optimal movements required the OT or PT to guide optimal movement by physically supporting their elbow as they moved. This was to ensure participants movement patterns were optimal and as near normal as possible when recording the kinematic data to set the lower bounds of the system.

Setting feedback thresholds

Feedback thresholds were then set for each of the three compensatory movement ML models in turn and individualised to suit the range of movement for each participant. An OT or PT supported the participant aiming for movement of the affected limb to be as near normal as possible. A precise threshold was stored in the system for the three supported positions (arm, trunk and shoulder) which, once exceeded, via compensatory movement, would trigger real-time feedback (muting of the music) until the participant corrected their posture, at which point the music continued. These feedback levels were typically in a range of 0.2 to 0.3 (i.e. 20 - 30% of the upper bound measurements) and always between the lower bound of 0.0 and the upper bound of 1.0.

5.2.2.4 Materials

The *Sonic Sleeve* system was run on an MSI GE72MVR 17.3" FHD Gaming Laptop running Ubuntu 16.04. A Logitech Full HD 1080 webcam was placed on an adjustable tripod to capture participants' movements which were mapped into the machine learning system. The webcam was positioned angling the camera at 2 o'clock or 10 o'clock relative to the affected arm of each participant. This provided optimal visibility for pose tracking during reaching movements while matching a natural therapist viewing perspective and reducing issues with occlusion and tracking accuracy (see Figure 5-2). A pair of standard PC speakers were used for all playback of music and a round 8cm diameter Walmeck plastic button was used to provide a physical target for the movements in the study. An electronic height adjusted table was used with additional cushions and towels to help therapists position the participant.

5.2.2.5 Procedure

The experiment took place in a research lab alongside the stroke unit during the second week of each participant's QSUL programme. All participants attended two 45-minute sessions after informed written consent was given (Appendix 5-2) and after being provided with a printed copy of the participant information sheet (Appendix 5-1). The first session was to help participants gain familiarity with the task and to train the system as described above followed 48 hours later by the main training session as shown in Figure 5-1. Prior to the first session, participants completed an auditory assessment to ensure that they were able to detect when the music was muted. For this, a sample of music was played and muted at random 10 times. All participants demonstrated that they could detect the onset and offset of the music sample by raising their non-affected arm to signal. To obtain data on possible covariates of interest, one measure relating to sleep, the St. Mary's Hospital Sleep Questionnaire and one relating to attention the sustained attention to response task (SART) as detailed by Robertson et al. (1997)were collected.

At the start of both sessions, participants filled out the St. Mary's Hospital Sleep Questionnaire. Sleep quality was assessed given its known impacts on cognition, mood, motor memory consolidation, and physical functioning (Ho et al., 2021) factors that could plausibly impact rehabilitation outcomes. In addition, at the end of each session participants rated their level of tiredness on a 5 stage Likert scale by answering the question: How tiring did you find taking part in this session? *[Not at all, a little, rather, very, extremely]*. After completing the study, most participants completed the SART (three participants were unable to complete this due to time constraints on the QSUL programme). During both study sessions participants undertook a seated active forward-reaching task (Figure 5-2). A single repetition began with the mid-point of the ulnar styloid positioned at the edge of the table with elbow in line with the centre of their torso on the hip. From here, participants moved their affected limb forward to a button attached to the table (set at an appropriate reaching distance by a PT or OT) before returning to the start position.

Familiarity Session

Each participant completed the initial familiarity session with a PT or OT from the QSUL programme, along with the researcher. Participants were supported into a position by the OT or PT to sit comfortably at the height adjusted table with cushions and towels available to ensure that they sat with their feet flat on the floor. The target button was then positioned at the most appropriate distance from the participant in front of their affected hand. The exact measurements were noted in a study spreadsheet to ensure consistency across sessions. Participants were then asked to move at a steady comfortable pace to reach and press the button at a speed that the PT or OT agreed was most suitable for their rehabilitation. A

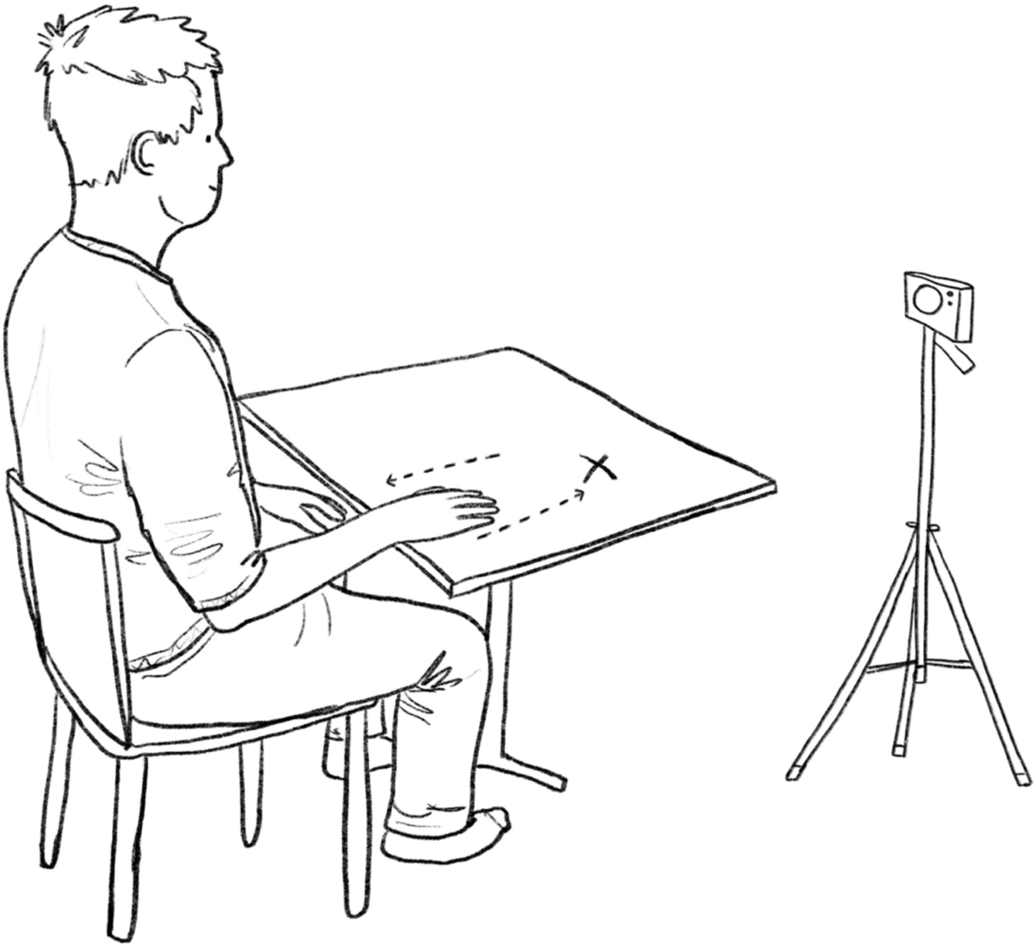

Figure 5-2: Participants were seated upright with their wrist on the edge of a height adjusted table. Participants moved their hand forward to reach a target button (marked with X) before returning to the original start position. A 2D webcam positioned at 2 o'clock/60 degrees relative to the participant collects video footage of their movement and sends kinematic data into a machine learning system.

metronome app was used to track the speed of movement with the researcher tapping the speed at the start position of the target movement and the button press position storing an accurate beat per minute (bpm), thus setting the individualised baseline tempo for each participant. Preselected music was loaded into the *Sonic Sleeve* programme matching the baseline tempo of each participant. Then the *Sonic Sleeve* system was used to record kinematic data providing the system with examples of each participant's movement pattern setting the upper and lower bounds and the thresholds for each participant separately as detailed above. The precise training steps with scripts are detailed in Appendix 5-5.

Participants then undertook 50 movement repetitions to practice using the system. After every 10 repetitions participants took a short rest of 10 seconds. Participants were told they did not need to move in time to the music but should focus primarily on movement quality, trying their best to perform the movements with their "best quality movement" possible. Pre-written scripts were read out by the researcher and available in clear bullet point large font print form for participants who required visual support (see Appendix 5-6). If the participants' movement included either trunk flexion, shoulder abduction, or shoulder elevation that the system could detect above the calibrated thresholds at any point they received feedback (muting of the music). Once they changed their posture based on having noticed the feedback, the music track then unmuted. Participants then chose 10 of their favourite pieces of music that would motivate them to perform the movement repetitions during the study. Of these, the researcher selected one that was closest to the participants' baseline tempo and prepared it for use in the main study session 48 hours later. Each audio file was edited using Audacity (https://www.audacityteam.org/) to ensure the music could automatically loop and retain a consistent tempo from the start to the end of the audio file. This ensured if a participant was in the middle of a reaching movement and the audio ended the music would not interfere with the movements of the participant.

Intervention Session

Participants positioned themselves in the target movement start position ready for the experiment to start with all apparatus positioned precisely as they had been for the familiarity session. In the condition with feedback (muting of music) participants undertook 50 repetitions of the target movement exactly as they had in the familiarity session. A longer rest of 2 minutes was taken between the two study conditions. There is a chance that carry-over effects may have taken place with those participants who received the feedback first achieving more time in optimal movement without the feedback. However, this was deemed an acceptable risk to take and each condition with 50 repetitions was of relatively short duration. In the control condition, participants were required to undertake 50 movement repetitions to the same self-selected music, but without any feedback to signal when compensatory movements occurred. Following the two conditions, participants reported their levels of tiredness.

5.2.2.6 Data Collection and Analysis

Data file outputs from the *Sonic Sleeve* system were processed in Python 3.7 (https://www.python.org) using JupyterLab (https://jupyter.org), and SPSS v24 was used to run the statistical tests. An independent t-test was run to assess the counterbalanced blocks for potential order effects. The dependent variable was the duration of compensatory movement as a proportion of total movement time. This was calculated for each movement repetition and then averaged across all 50 repetitions, for each condition (with feedback; without feedback). A repeated measure ANCOVA compared the dependent variable across the two blocks, while controlling for any overall differences in movement speed across conditions to address the primary aim for Experiment 1A.

To address the secondary research aims for Experiment 1A the relationship between response to feedback and the clinical baseline measures (see Table 5-1) and the SART scores were assessed with Spearman's rank tests and Mann-Whitney U tests were run between the 10 highest responders to feedback and the 10 lowest responders on the 14 clinical baseline variables. Bonferroni correction (*p*<.05/14=.004) was used to control for multiple comparisons. Further Wilcoxon signed-rank tests were run at the individual participant level due to deviations from normality.

5.2.3 Results

Participant demographics and clinical characteristics are summarised in Table 5-1. There was no main effect of block order; t(18) = 0.759, *p*=.461. As seen in Figure 5-3, the duration of compensatory movement with feedback was 19.3% (SD 18.7%; 95% CI 11.3%-27.3%) compared to without feedback 39.4% (SD = 26.5%; 95% CI 27.5%- 51.4%). This was a statistically significant difference, F(1,18) = 9.424, *p*=.007, with a large effect size (partial η^2=.344; *f* = .717) based on Cohen (1988) for small, med and large effects of *f* = 0.10, 0.25, and 0.40. Using Cohens *f* has recently been recommended for interpreting ANCOVA effect sizes (Shieh, 2023). No associations were found between the magnitude of compensatory movement reduction and clinical baseline variables (p>.05). Similarly, the between group tests comparing the 10 highest responders to feedback with the 10 lowest responders on all 14 clinical baseline variables were nonsignificant (p>.05). Further no significant associations were found between the primary outcome variable and the two study specific items (Table 5-2), namely the tiredness rating and SART scores (p>.05).

Individual participant level analyses

14 participants showed significant reductions in the duration of compensatory movement with feedback (Figure 5-4). Three participants showed no statistically significant difference between conditions and the remaining three participants showed a significant increase in the duration of compensatory movement with feedback. As seen in Table 5-2 the SART scores show little variance across participants with all participants achieving a low error rate. No participants reported any concerning issues with sleep as evidenced in the questionnaires taken pre-session with the majority of participants rating the sessions as a little

tiring with one session rated as 4 (very tiring). However, this rating did not affect the ability of the participant to achieve the 100 reps.

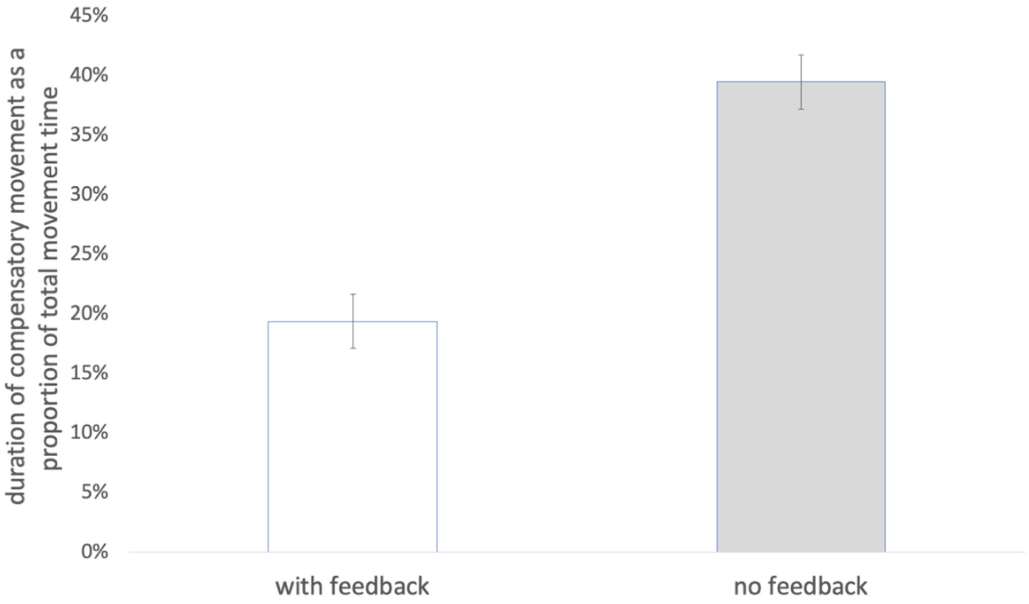

Figure 5-3: The duration of compensatory movement as a proportion of total movement time for 20 participants undertaking 50 repetitions with feedback compared to 50 repetitions with no feedback. Error bars are adjusted 95% CI removing between-subject variability.

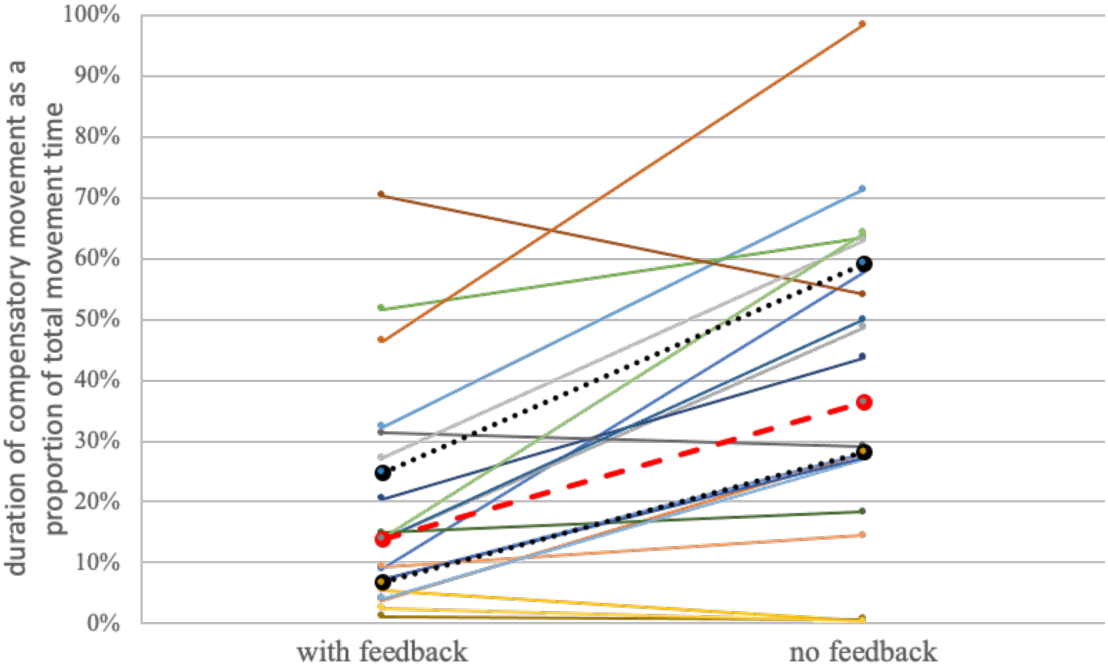

Figure 5-4: The duration of compensatory movement as a proportion of total movement time for 20 participants who provided full datasets (with and without auditory feedback). Median (dashed line), upper and lower quartiles (dotted lines) are shown.

Table 5-2: Intrasubject non-parametric tests and study specific items

Participant ID (n=20)	*Median*** with feedback	*Median*** no feedback	Z	*Median* diff	*p*-value	effect size	Trials (N)	Tiredness (1-5)	SART (Max = 255)
1	0.02	0.51	-5.79	-0.44	<.001*	0.58	98	3	na
2	0.00	0.24	-4.66	-0.23	<.001*	0.47	98	2	na
3	0.08	0.45	-4.62	-0.34	<.001*	0.46	100	2	198
4	0.00	0.00	-3.50	0.00	<.001†	0.37	100	2	204
5	0.27	0.73	-5.41	-0.37	<.001*	0.55	98	1	214
6	0.47	0.68	-1.98	-0.13	=.047*	0.21	100	4	221
7	0.16	0.47	-3.77	-0.25	<.001*	0.37	100	3	209
8	0.75	0.50	-2.40	0.09	=.016 †	0.26	100	2	199
9	0.24	0.30	-0.11	0.00	=.914 ø	0.01	96	1	209
10	0.00	0.00	-0.51	0.00	=.612 ø	0.05	100	1	218
11	0.06	0.48	-4.89	-0.31	<.001*	0.53	100	2	219
12	0.04	0.09	-0.78	0.00	=.435 ø	0.07	100	2	204
13	0.00	0.11	3.82	-0.01	<.001*	0.38	100	2	223
14	0.06	0.14	2.47	-0.04	=.013*	0.28	100	2	221
15	0.16	0.72	4.46	-0.30	<.001*	0.47	100	1	190
16	0.00	0.00	2.39	0.00	=.017†	0.24	100	2	210
17	0.00	0.26	5.82	-0.21	<.001*	0.58	100	2	222
18	0.09	0.72	5.67	-0.58	<.001*	0.57	98	2	217
19	0.00	0.27	4.52	-0.21	<.001*	0.45	100	2	204
20	0.41	1.00	5.84	-0.58	<.001*	0.58	100	2	na
							99.4(*Mean*) 1.14(*SD*)		211 (*Mean*) 10(*SD*)

*Note: na = data not available due to time constraints in the participants' rehabilitation schedules; * = significant reductions in the amount of time in compensatory movement with the feedback at the .05 alpha level; † = significantly more time in compensation with feedback; ø = no difference between conditions; SART = sustained attention to response task; ** = median duration of compensatory movement as proportion of total movement time; Tiredness = 5 stage Likert scale taken immediately post intervention answering the question: How tiring did you find taking part in this session? [Not at all, a little, rather, very, extremely].*

5.2.4 Discussion

Experiment 1A assessed a digital approach to upper limb rehabilitation with a focus on quality of movement. Participants performed an active forward reach task while listening to self-selected, favourite music and received feedback (muting of music) to guide them towards more optimal movement patterns, and therefore away from unwanted compensatory movements. At a group level, participants reduced the duration of compensatory movement as a proportion of total movement time by 20.1%. In addition, at an individual participant level, 14 of 20 participants achieved statistically significant reductions in this same measure. The large effect size achieved is comparable to prior research providing real-time force and visual (Valdés & Van der Loos, 2018).

The primary aim of Experiment 1A was to assess whether real-time auditory feedback, provided through muting of music, could reduce the duration of compensatory movements compared to a condition without feedback in a controlled environment. The secondary aim was to explore potential relationships between response to feedback and clinical baseline and no statistical significance was found warranting further investigation with larger samples. Together with the within-subject design minimising confounds, the quantitative indicators provide evidence that participants could leverage the auditory feedback to increase their time in optimal movements, directly addressing the core research question. Follow-up insights on participants' experience using questionnaires or other qualitative methods would help to further the research findings. However, most participants succeeded in making use of the feedback to increase their time in optimal movement patterns. While further subjective feedback is warranted, the study sufficiently demonstrated through quantitative outcomes that participants can utilise the auditory feedback to minimise compensatory movements.

There was notable variability in participants' ability to utilise the auditory feedback. While most participants achieved statistically significant reductions in compensatory movements, a subset of non-responders showed no difference or an increase in compensation duration when feedback was present. Further investigation could elucidate factors differentiating responders from non-responders. Several factors likely contributed such as demands from monitoring and modulating concurrent feedback on multiple compensation types may have exceeded cognitive capacity for some, restricting self-corrections. The auditory feedback detected and signalled compensation stemming from three distinct types – shoulder abduction, shoulder elevation and trunk flexion concurrently. Having to monitor and modulate compensations may have increased perceptual, attentional and correction demands, increasing cognitive load. This dual task element may explain why some of the participants did not achieve reductions with the feedback being too challenging and not matching to their current abilities; as highlighted in Challenge Point Theory, rehabilitation should progress with the abilities of the individual tailored to the current skill levels of the individual and progress tasks creating optimal challenge (Guadagnoll & Lee, 2004).

Non-response may also be explained by tracking limitations from relying solely on a 2D webcam for motion quantification likely reduced accuracy. This issue may be more general across the system as a recent scoping review highlights the challenges of using markerless tracking with the underlying machine learning models and datasets not designed and trained for clinical applications (Wade et al., 2022). Sensor fusion from supplementary inexpensive devices such as wearables could enhance measurement fidelity (Bai et al., 2020). Combining data from additional inexpensive sensors like wearable IMUs could have provided more robust movement quantification, enhancing detection and the robustness of the feedback. Another reason for non-responders could be that the analyses focused narrowly on compensation duration; those who appeared non-responsive may have exhibited uncaptured coordination/quality improvements such as smoothness of movement (Scholz et al., 2016).

Additionally, the brief protocol likely provided insufficient repetitions for significant motor learning, as highlighted in animal models of learning by Kleim et al. (1998) and Nudo et al. (1996) that suggest hundreds of daily practice trials are often required to drive cortical reorganisation underlying sustained capability gains. The current paradigm may therefore have served more as an initial evaluation of compensation reduction rather than full training regimen. As Schmidt & Lee (2019) discuss, temporary performance enhancement via feedback does not necessarily produce lasting motor learning without retention. Hence, while the feedback may have briefly reduced compensation duration during blocks, lack of more permanent gains could signify challenges fully utilising the concurrent input. It is possible that motor learning occurred which was not captured in the performance measurements.

Another limitation of the study was that participants' levels of tiredness were not assessed after each experimental condition separately. This prevented a direct analysis between the with feedback condition and the no feedback condition. In future research, it would be beneficial to collect tiredness data after each experimental block to gain a more nuanced understanding of the potential fatigue effects associated with specific conditions.

While prior research using real-time feedback has focused on only one source of compensatory movement – trunk flexion (Valdés et al., 2017) *Sonic Sleeve* can detect compensation from two other common compensatory movement patterns: shoulder abduction and shoulder elevation. While the current study used a single signal to convey compensatory movement from any of these three sources, a future version could, in principle, use different forms of auditory feedback to differentiate compensatory movements coming from each of the three sources, providing a more nuanced feedback signal. As the first iteration of *Sonic Sleeve*, a simple binary manipulation was used, particularly to ensure that the feedback would always be salient given possible perceptual and/or cognitive impairments, but several different parameters of the music could, in principle, be flexibly mapped onto different movement components.

Self-selected music is considered more meaningful to participants than experimenter selected music (Sihvonen et al., 2017) and provides a motivational framework that can make rehabilitation more enjoyable (Wylie, 1992). In addition to the personal choice that this approach allows, the temporal structure present in almost all music is also a relevant feature. Rhythmic entrainment (our ability to synchronise with the beat of the music) has been linked to strong activations of the auditory and motor regions of the brain (Zatorre et al., 2007) and forms the basis of rhythmic auditory cueing (RAC) (Thaut et al., 1996), one of the most widely used approaches for music in neurorehabilitation (Magee et al., 2017). A protocol devised by van Wijck and colleagues combined self-selected music and RAC using a 'tap tempo' paradigm for upper limb rehabilitation with participants required to reach targets in time to the music (Van Wijck et al., 2012). In contrast, in the current study, participants were not constrained to entrain to the beat as is the case with RAC because participants were explicitly told to focus predominantly on reducing compensation rather than trying to keep in time with the music. Nevertheless, the presence of a ‘beat’ was potentially helpful in driving the movement and in our prior research participants achieved hundreds of repetitions every session playing bespoke drum pads as part of a home-based rehabilitation programme (Kirk et al., 2016).

The current study used a single piece of music matched to the participants’ baseline tempo, but a more varied playlist could be created for long term rehabilitation to keep interest and encourage variation in the speed of movements. The combination of a motivational medium (self-selected music) with a feedback signal to guide movement towards a more optimal pattern represents a promising approach to focusing on both dose and quality. Rehabilitation training for the upper limb in humans is typically at far lower levels (Lang et al., 2009) when compared to animal models where many hundreds of daily repetitions are reported. Systems such as *Sonic Sleeve* can potentially help stroke participants attain comparably high doses while still focusing on movement quality. Experiment 1B below deploys the *Sonic Sleeve* system moving from the lab setting into the home environment and assesses the feasibility of participants receiving auditory feedback from an off the shelf motion tracking system in the home. Future iterations of *Sonic Sleeve* could also be run off a tablet or smart mobile phone camera lending itself to the home environment at even lower cost.

5.3 Experiment 1B: Sonic Sleeve in the Home

5.3.1 Aims

Experiment 1B aimed to extend and replicate the findings from Experiment 1A into the home environment. The 100-repetition protocol from Experiment 1A was run multiple times without a therapist or researcher being physically present permitting further analyses with more ecological validity. Additionally, a post-study questionnaire was created specifically for the research addressing the feasibility of using the rehabilitation technology in the home covering practicalities of setting up and device use alongside questions aiming to understand participants' views on the Sonic Sleeve @ Home App and the acceptability of the technology.

5.3.2 Materials and Methods

5.3.2.1 Study Design

Participants completed three within-subject sessions at home, spaced a week apart, consisting of two blocks (with feedback vs. without feedback) using the same randomisation and counterbalancing approach as Experiment 1A above for the first session and then reversing the starting condition each subsequent session.

5.3.2.2 Participants

All participants taking part in Experiment 1B were enrolled on a new online pilot version of the QSUL neurorehabilitation programme as a direct response to Covid-19. This was similar to the standard QSUL programme, but participants had daily telerehabilitation sessions with therapists over a 4-week period. Participants physically attended the stroke unit one day in their first week. Ten participants were screened (see Figure 5-5) with the same inclusion criteria as those for Experiment 1A. Two participants had too much chronic fatigue to take part, one was unable to attend due to timetabling issues, one participant could not be included in the study due to a data collection failure, one participant could not physically plug in the equipment in his home and one participant could not take part due to a family matter. This left four participants with chronic stroke who took part in the study and completed all sessions successfully. Written informed consent was given by all participants when they were in the stroke unit and full ethical approval was attained with substantial NHS ethics amendments (see Appendix 5-7) granted to permit the home-based data collection by the London Dulwich research ethics committee (ref: REC 19/LO/0579). Further Covid-19 permissions were attained via the Infection Prevention and Control Framework (ICP) at UCLH ensuring infection prevention and control was assessed for the research. Table 5-3 shows participant details, including scores on a range of clinical measures that were assessed[6].

Table 5-3: *Demographic and clinical characteristics of 4 participants from Experiment 1B*

Patient ID (n=4)	Gender (M=75%)	Age (years)	AL (R=85%)	DH (R=75%)	TSS (months)	mRS Max=5	BI Max=20	FM-UL Max=54	Impairment Level	CAHAI Max=91	Arm-A Max=28	Arm-B Max=52	Apraxia (No=100%)
21	F	48	R	L	53	NA	18	51	mild	50	3	13	No
22	M	43	L	R	22	NA	20	24	moderate	26	8	30	No
23	M	64	L	R	14	3	17	35	moderate	NA	0	28	No
24	F	51	L	R	46	3	18	23	moderate	16	0	27	No
Mean(SD)		52(9)			34(19)	3(0)	18(1)	33(13)	(mild=25%)	31(17)	3(4)	25(8)	

Abbreviations: AL = affected limb; DH = dominant hand; TSS = time since stroke; mRS = modified Rankin Scale; BI = Barthel Index; FM-UL = modified upper limb Fugl-Meyer; CAHAI = Chedoke Arm and Hand Activity Inventory; ArmA = Arm Activity Measure, na = data not available

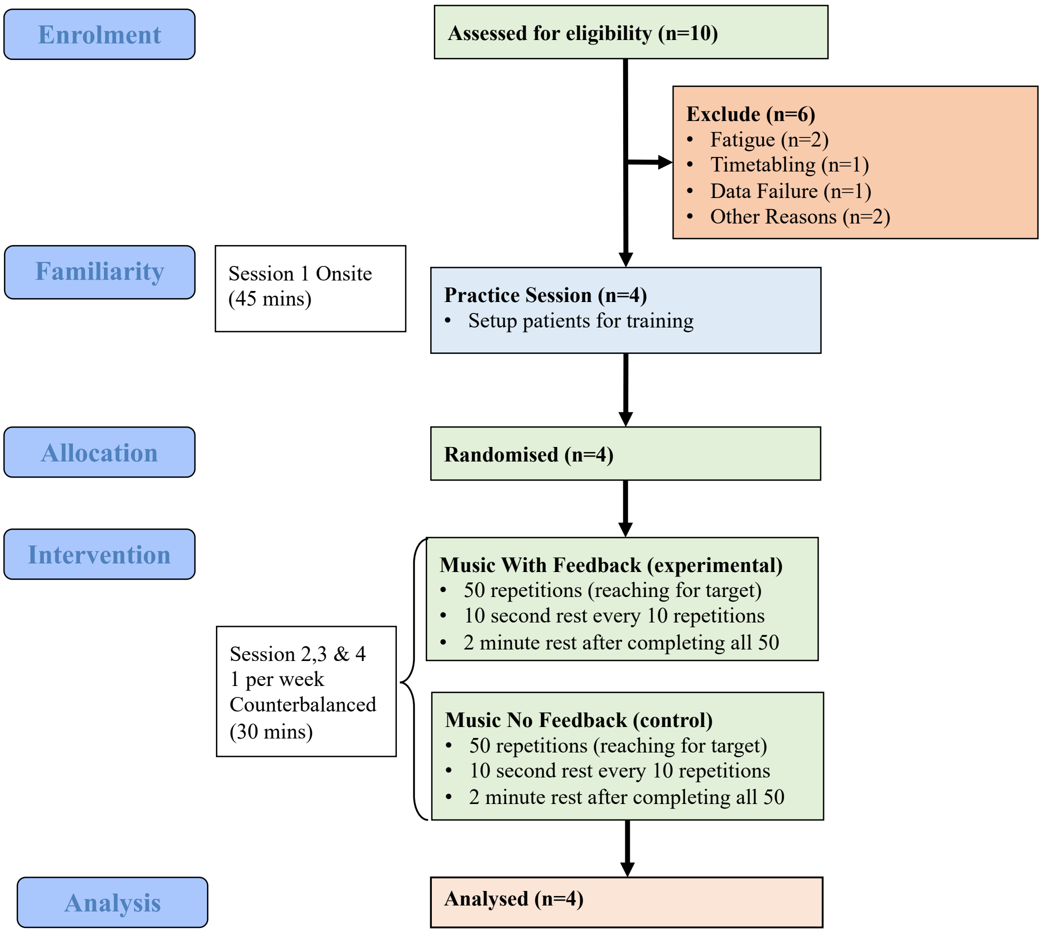

Figure 5-5: Flow diagram of participant progress through Experiment 1B

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[6] Time constraints on the QSUL online programme due to Covid-19 meant less clinical baseline measures were taken.

5.3.2.3 Description of the Sonic Sleeve @ Home System

The Sonic Sleeve @ Home system used for Experiment 1B was similar to the version from Experiment 1A with some specific technical differences. The system works without a therapist or researcher needing to be in the same room as the participant. Every participant attending the Online QSUL programme was offered a specialist Rehab Kit (from the company Evolv Rehab™) to undertake telerehab exercises in the home by playing a range of immersive games. Sonic Sleeve @ Home was deployed as a stand-alone App on the Rehab Kit using an in-built camera – the AZURE Kinect from Microsoft. This depth camera permitted the tracking of participants' movements in 3D. Four x, y, z sets of co-ordinates were derived from the participants' affected limb: neck, wrist, elbow, and shoulder and mapped to sound using a new machine learning library called InteractML[7] (Hilton et al., 2021)based on the RapidLIb application programming interface (API) (Zbyszynski et al., 2017) in Unity, a game development platform on Windows 10. Setting the upper and lower bounds for the system and the feedback thresholds followed a similar protocol to those described in Experiment 1A above (section 5.2.2.3). As in Experiment 1A the *Sonic Sleeve* system training and calibration took place on the stroke unit in person with therapists and participants. No calibration took place in the home environment for Experiment 1B. There were some minor alterations due to the different technological implementation. Key differences related to the fact that, in the home-based version, participants reached up to a virtual target displayed on a TV monitor rather than reaching for a physical button placed on a table (see Figure 5-6).

5.3.2.4 Procedure

Participants were provided with an updated information sheet for the at home study (see Appendix 5-9) prior to giving informed consent. All participants completed a single 45-minute familiarity session in the clinic during week 1 of their online QSUL attendance followed by three 30-minute sessions (Figure 5-5) conducted over a Zoom Clinical account in their own homes. The three sessions at home were timetabled to fit between numerous OT and PT

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[7] http://interactml.com/

therapy sessions. At the end of each session participants rated their level of tiredness on a 5 stage Likert scale by answering the question: How tiring did you find taking part in this session? *[Not at all, a little, rather, very, extremely]*.

Participants sat on any chair that was available permitting a comfortable start position with their feet flat on the floor for stability with the chair positioned 1.5m back from the AZURE Kinect camera. A single repetition began with the participant resting both their hands on their knees with their elbows in line with the centre of their torso on the hip. From here participants lifted their affected limb up and forward to a target position set by an OT or PT before returning to the start position. This target position was stored as a virtual bullseye target on screen (Figure 5-6). The target on screen was highlighted in RED unless the participants' hand was in the target position signalled by the virtual target turning GREEN. As soon as the hand moved outside the target position the target would return to RED. In this way a participant could easily see if they reached the correct target position when the therapist and researcher where not physically present. A few days before participants attended their first rehabilitation session on the stroke unit, they had a phone consultation with the researcher and gave a list of 10 of their favourite songs. The bpm of each song was noted and the song with the most relevant tempo was prepared for the familiarity session that took place when they attended their first physical session on the QSUL programme.

Familiarity Session

Each participant completed the familiarity session with a PT or OT from the QSUL programme, along with a researcher. Participants were shown a brief demonstration of the system working by the researcher. Participants then sat on a chair with their feet flat on the floor. The OT or PT helped ensure the participant could hold their affected hand in a relevant target position for 5 seconds. This hand position was recorded, and the coordinates were stored in the App giving the individualised position for the virtual target shown on the TV monitor. The start position of the hand was also recorded giving the system the ability to count

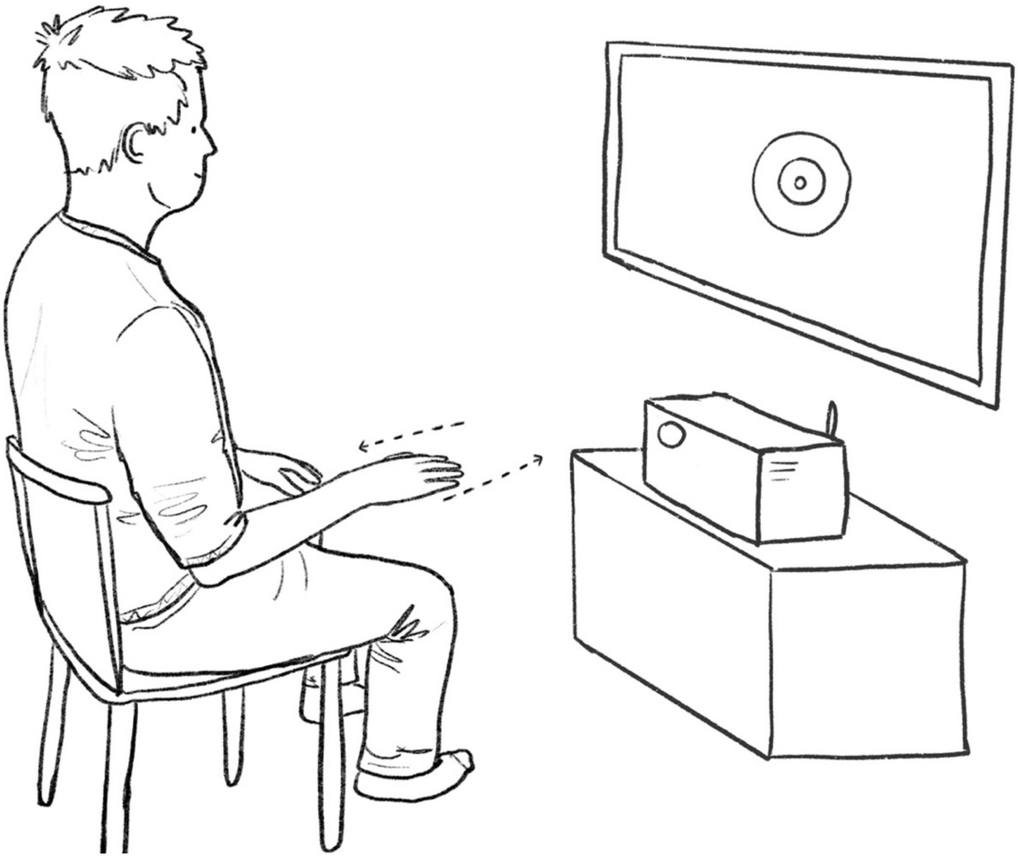

Figure 5-6: The participant seated upright 1.5m back from the Rehab Kit camera in front of their home TV. Their hands start resting on their knees with the elbows in line with their hip before reaching up and forward with their hand to a virtual target on the TV screen. Despite the Rehab Kits being placed at a range of different heights relative to the participants the data was collected with good acuity with adaptive positioning built into the Sonic Sleeve @ Home App.

the number of repetitions between the start and target position and trained using a K-Nearest Neighbor (KNN) ML algorithm. The current repetition number was displayed on screen counting up to 10 for each exercise block. Participants were asked to move at a steady comfortable pace from their start position to reach forward to the target position and back to their start position while listening to their favourite self-chosen music. The *Sonic Sleeve @ Home* system was used to record kinematic data providing the system with examples of each participants' movement pattern which was used to set the individual upper and lower bounds and the thresholds for each participant.

Participants then undertook around 10 movement repetitions to practice using the system. Participants were told they did not need to move in time to the music but should focus primarily on movement quality, trying their best to perform the movements with their “best quality movement”. As with the previous experiment, if the participants’ movement included either trunk flexion, shoulder abduction, or shoulder elevation above the predetermined thresholds, the system provided auditory feedback to the participant (muting of the music track).

Intervention Sessions

Participants attended all three sessions by logging into Zoom as they were for all other virtual therapy sessions. A clinical “breakout room” on Zoom was used for the researcher to monitor the session and help guide the participants through the experiment. Participants used a wireless trackpad to launch the Music App. A script was read out reminding participants of their start position and explaining that they were to move with the best quality movement that they could, just as they had in the familiarity session. Once the participant was comfortable with the instructions, they used the wireless trackpad to start the experiment with a single button press. The app was designed to be as simple as possible to navigate and use with the only participant interaction required being i) the app launch and ii) pressing the start button; no other physical interaction with the wireless trackpad was required. Once the experiment started participants had 5 seconds to get ready with large numbers counting down on screen. As soon as they heard the music start playing, they started to reach forward for each repetition. In the condition with auditory feedback participants were required to undertake 50 repetitions of the target movement while listening to a self-selected favourite piece of music which matched their baseline movement tempo. If a participant used compensatory movement, such as trunk flexion or shoulder abduction, the Sonic Sleeve @ Home system automatically muted the music until they corrected their posture. After every 10 repetitions participants took a short rest of 10 seconds with a countdown timer on screen in seconds. A longer rest of 2 minutes was taken between the two study conditions again with the seconds counting down on the screen. In the control condition, participants were required to undertake 50 movement repetitions to the same self-selected music, but without any feedback to signal when compensatory movements occurred. As soon as participants completed 100 repetitions the app automatically closed down saving the data. Participants were asked to rate their level of tiredness, and this completed the session. Participants repeated this same procedure once a week for three weeks.

Post study questionnaire

The post-study questionnaire (see Appendix 5-8) was designed by the research team including the PhD candidate, supervisors (Prof Stewart, Prof Grierson) and the principal investigator on site neurologist (Prof Ward). Questions were informed by established usability models including the System Usability Scale (SUS) (Brooke, 1996), Intrinsic Motivation Inventory (IMI) (McAuley et al., 1989), and Technology Acceptance Model (TAM) (Hu et al., 1999) to assess usability, motivation, and technology acceptance factors respectively. Items on the questionnaire linked to SUS included learnability, usability and confidence using the system. From the IMI, questions addressed interest/enjoyment, perceived competence, and effort. Finally, elements from TAM included perceived usefulness, perceived ease of use and intention for future use. While not specifically validated, this tailored questionnaire aimed to gather targeted insights around feasibility and experiential aspects of using the novel *Sonic Sleeve* @ Home system in participants' homes.

The questionnaire was administered within 24 hours of completing the study over the phone. All four participants answered 18 questions about their home-based situation and their experience of using the *Sonic Sleeve @ Home* App in the home environment. The first 17 questions were either yes/no or 5 stage Likert scales with a final open-ended question to allow participants to comment on any other aspect of the study (see Appendix 5-8 for the full questionnaire).

5.3.2.5 Data Collection and Analysis

All movement data were collected directly onto the Rehab Kits assigned to each participant when they attended the online QSUL programme between August 2021 and November 2021. Data file outputs from the *Sonic Sleeve @ Home* system were processed in Python 3.7 (https://www.python.org) using JupyterLab (https://jupyter.org), and SPSS v24 was used to run the statistical tests. As in Experiment 1A, the dependent variable was the duration of compensatory movement as a proportion of total movement time, calculated for each movement repetition and averaged across all 50 repetitions. Effect of block order was assessed using an independent t-test. Paired samples t-tests assessed whether the presence of auditory feedback reduced the proportion of time spent in compensatory movement separately for each of the three sessions at home and for all three sessions combined. Further Wilcoxon signed-rank tests were run at the individual participant level due to deviations from normality. A diary was kept by the researcher to track session reports and note any adverse events. If any adverse event was reported by a participant or noted in a session by the researcher it was to be reported to the staff on the QSUL programme as soon as possible to follow the Reporting of Adverse Events Policy which includes immediate notification of the participants' care team, documenting the event in the electronic health record, and submitting an incident report within 24 hours. Results from the post-study questionnaire were analysed using descriptive statistics and extracting key qualitative statements that came up during the administration of the questionnaire.

5.3.3 Results

Participant demographics and clinical characteristics are summarised in Table 5-3. No adverse events were reported during the study. There was no main effect of block order across the three sessions; t(10) = 1.920, *p*=.084. The duration of compensatory movement with feedback was lower for each of the three sessions at the group level and these differences were not statistically significant as seen in Table 4-4 below (all p > .05). All three sessions had a difference between conditions of around 15% as shown in Figure 5-7 below. However, when combining all three sessions into one analysis the participants significantly reduced the proportion of time with feedback (21.68% ± 12.86%) compared to without feedback (37.32% ± 22.55%), a reduction of 15.64% (95% CI, 6.34% to 24.88%), t(11) = 3.722, *p*=.003, with a large effect size *d*=1.07 as seen in Table 5-4 below. No adverse events were reported during the study.

Table 5-4: *Descriptive statistics and results of t-tests comparing three individual sessions* and combined sessions data *with feedback vs. without feedback*

Group	M	SD	*t*(df)	*p*	95% CI		Cohen's d
					LL	UL	
S1 With Feedback	0.23	0.90	-2.295(3)	.105	-.389	.063	0.142
S1 No Feedback	0.39	0.16					
S2 With Feedback	0.20	0.20	-1.883(3)	.156	-.440	.113	0.173
S2 No Feedback	0.37	0.31					
S3 With Feedback	0.22	0.11	-1.738(3)	.181	-.404	.119	0.164
S3 No Feedback	0.36	0.24					
SC With Feedback	0.22	0.13	3.722(11)	.003	.064	.249	1.07
SC No Feedback	0.37	0.23					

Note: M = mean, SD = standard deviation, t = test statistic of the independent samples t-test, p = probability value, CI = confidence interval, LL = lower limit, UL = upper limit, S = session number, SC = sessions combined (S1+S2+S3)

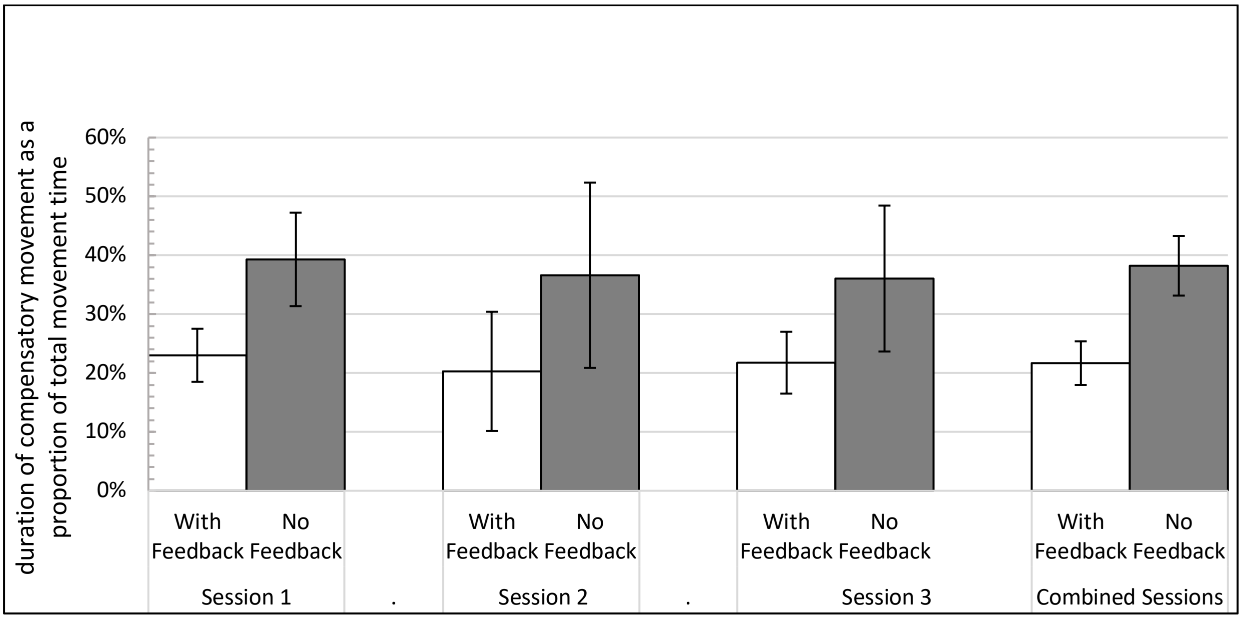

Figure 5-7: The duration of compensatory movement as a proportion of total movement time for 4 participants undertaking 50 repetitions with feedback compared to 50 repetitions with no feedback over three sessions and combined (far right). Error bars are standard error.

Individual participant level analyses

When comparing the three sessions at the individual level variability was noted (see Figure 5-8 below). Participant 1 and 3 showed significant reductions across all three sessions with participant 4 having a similar significant reduction in session 1 and 3 but not session 2. Participant 2 was performing with low levels of compensation and did not show any significant reduction of compensatory movement with feedback. Tiredness ratings and statistical test values for all sessions are shown in Table 5-5 below.

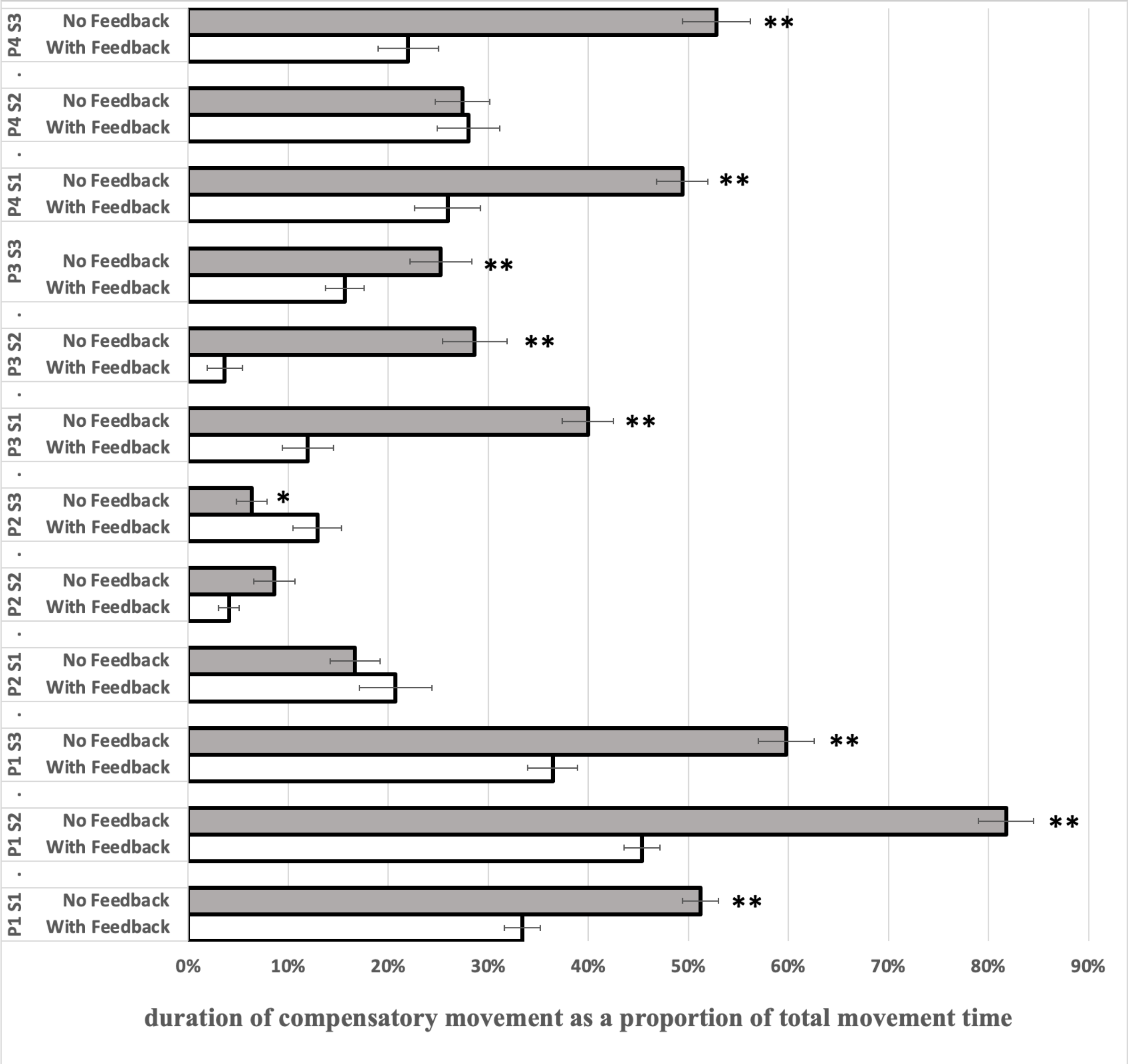

*Figure 5-8: The duration of compensatory movement as a proportion of total movement time for 4 participants undertaking 50 repetitions with feedback compared to 50 repetitions with no feedback across all three sessions at the individual level. P = participant, S = session number, ** = significant (p < .05). Error bars are standard error.*

Table 5-5: *Intrasubject non-parametric tests and tiredness ratings post intervention*

Participant ID (n=4)	*Median*** with feedback	*Median*** no feedback	Z	*Median* diff	*p*-value	effect size	Tiredness S1 (1-5)
P1 S1	0.37	0.54	5.19	-0.18	<.001*	0.52	2
P1 S2	0.43	0.87	5.70	-0.35	<.001*	0.57	3
P1 S3	0.31	0.65	4.48	-0.27	<.001*	0.45	1
P2 S1	0.09	0.10	-0.04	0.35	=.725 ø	0.04	1
P2 S2	0.00	0.00	1.41	0.00	=.158 ø	0.14	1
P2 S3	0.06	0.00	2.18	0.04	=.029†	0.22	1
P3 S1	0.06	0.42	5.64	-0.34	<.001*	0.56	2
P3 S2	0.00	0.28	4.89	-0.26	<.001*	0.49	2
P3 S3	0.14	0.17	2.12	-0.06	=.034*	0.21	1
P4 S1	0.19	0.50	5.01	-0.24	<.001*	0.50	2
P4 S2	0.25	0.27	0.22	0.01	=.823 ø	0.02	2
P4 S3	0.14	0.55	4.93	-0.39	<.001*	0.49	3

*Note: P = Participant; S = session number; * = significant reductions in the amount of time in compensatory movement with the feedback at the .05 alpha level; † = significantly more time in compensatory movement with feedback; ø = no difference between conditions. ** = median duration of compensatory movement as proportion of total movement time; Tiredness = 5 stage Likert scale taken immediately post intervention answering the question: How tiring did you find taking part in this session? [Not at all, a little, rather, very, extremely].*

Post-study questionnaires

The answers to the first 6 questions were all yes/no and centred around basic setup of the rehabilitation device and are listed in Figure 5-9 below. One participant lived alone, and all four participants stated they were comfortable accessing the internet which was essential for them to join the rehab sessions via video link. Half the participants required a family member or carer to setup the rehab kit as it was too challenging to do alone.

Technical support to access the video link for session monitoring was required and some participants required support to setup the Wi-Fi for the rehabilitation device. All 4 participants rated their Wi-Fi connection as stable every time they had a session. However, two participants stated that they were never able to resolve technical issues that arose (see Figure 5-10 Q8).

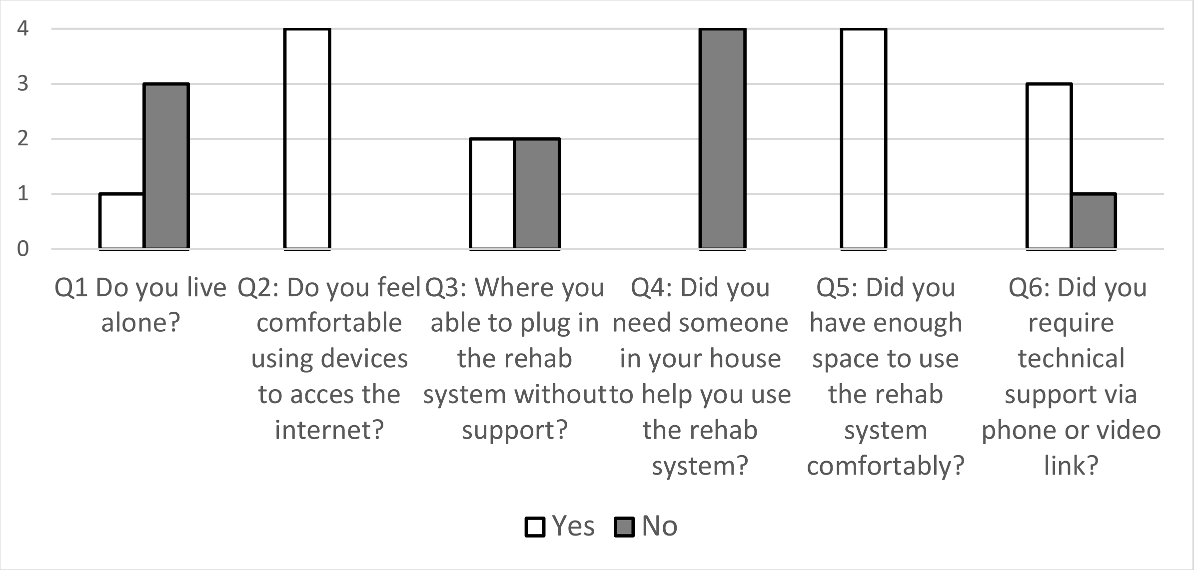

Figure 5-9: Responses to yes/no questions around living conditions and setup of the Rehab Kit by 4 participants.

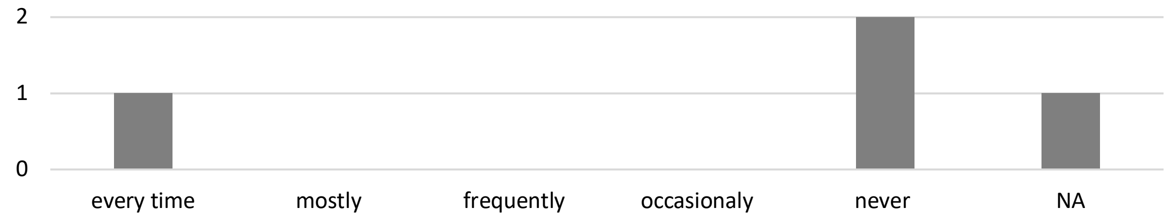

Figure 5-10: Q8: When technical issues arose, I could resolve them

One participant was more confident, and another had no technical issues at all over the intervention period. The two participants who rated *Never* stated this was due to not being able to connect to Wi-Fi to join the rehabilitation sessions without telephone support from the researcher. Once the rehabilitation device was setup no participant required any support to launch the Sonic Sleeve @ Home App and run the experiments. Two further questions relating to setup and usability were rated as very easy by the majority of participants (Figure 5-11).

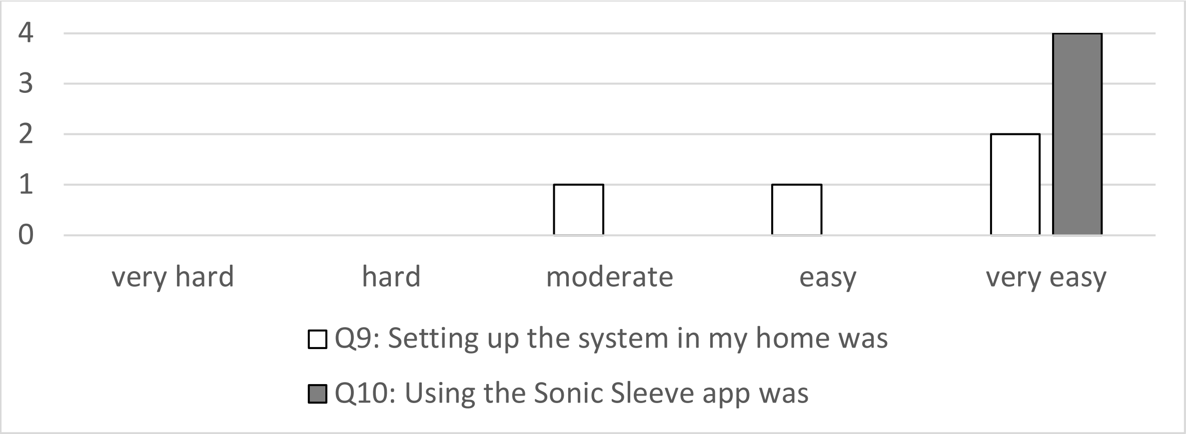

Figure 5-11: Participants responses to Q9 and 10.

The final five Likert scale questions (Q11-Q15) were linked directly to the intervention and are displayed in Figure 5-12.

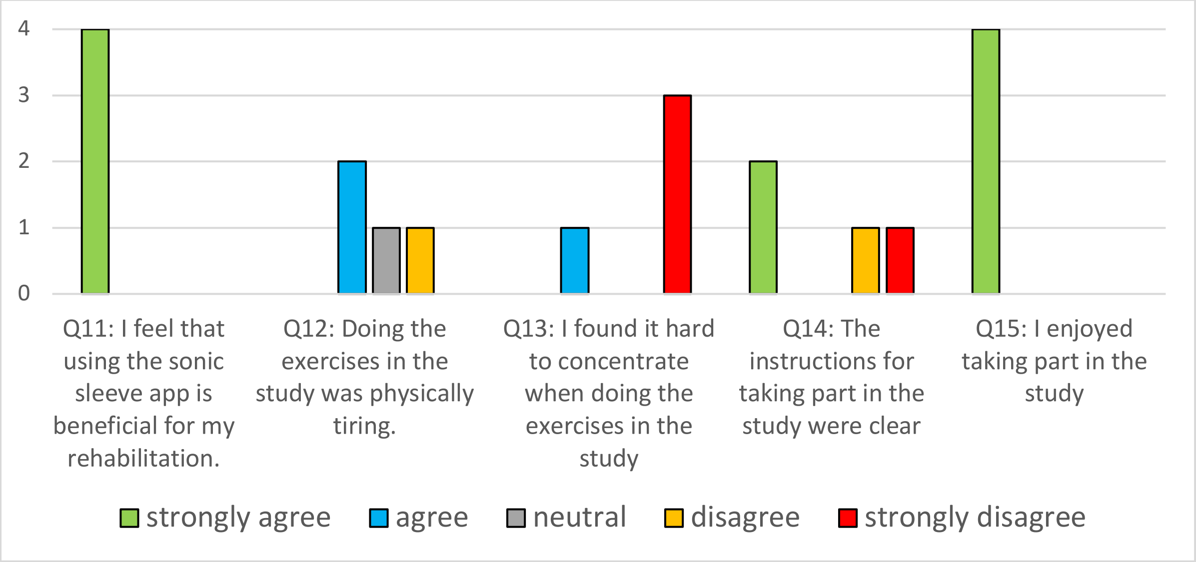

Figure 5-12 Four participants' responses to questions 11-15. The rating of strongly disagree to Q14 about the instructions being clear was rated by a participant with severe aphasia.

Qualitative feedback

All participants gave verbal feedback about the system with general comments. P1 who had severe aphasia found the exercises somewhat physically tiring often rating her tiredness as “not at all tiring” but she did struggle with concentration at times stating, “Aphasia is very hard.”

She stated that 1 song for the study was okay but that a playlist would be better for long-term engagement. Her affected limb impairment was quite mild and she also stated that she would like to see more challenge in the App:

> *“A playlist would be better than one song.”*
>
> *“There needs to be progression – make it adaptive.” Stroke P1*

P2 did not have any other comments about taking part in the study other than one comment that the Microsoft Windows 10 updates should be forced into the background as they interrupted the gameplay occasionally interfering with the rehab time when he was playing the commercially available games on the device. However, this issue did not arise during the participants’ use of the *Sonic Sleeve @ Home* App.

P3 raised the limitations of having one song only for many repetitions in the study and remarked in surprise that he was not irritated by the song:

> *“Be careful about the choice of music. This has worked out very well. I thought I would be irritated by the music track over time, but I was not.” Stroke P3*

They were highly complementary of the *Sonic Sleeve @ Home* App and recommended it verbally backing up the Likert scale question above:

> *“I definitely recommend it to participants in a similar situation as mine. Most stroke participants actually. It is really good rehab – really good.” Stroke P3*

They did mention that the Rehab Kit was not optimal for many stroke participants.

> *“The slight irritation is the heaviness of the kit. It could be streamlined.*
>
> *If you are not as mobile as I am.” Stroke P3*

Stroke P4 did not have any other comments about taking part other than to say the HDMI cable was very difficult to connect. The inability to attach the HDMI cable from the Rehab Kit to the TV was also the primary reasons that one participant was excluded from the study.

5.3.4 Discussion

Experiment 1B further developed the initial experiment by deploying *Sonic Sleeve* directly in stroke participants' homes. At a group level, participants reduced the duration of compensatory movement as a proportion of total movement time by 15.64%. This reduction was comparable across all three individual sessions at the group level. Experiment 1B corroborates and illustrates a successful replication of the findings in Experiment 1A in a more ecologically valid location, namely the home environment where the majority of stroke participants ongoing rehabilitation takes place. At the individual level most sessions saw significant reductions in the proportion of time in compensatory movement. However, variability in the data and some floor effects highlighted the challenge of tracking participants over time as similarly found in Experiment 1A.

The lack of a significant effect at the individual session level is likely due in part to the small sample size. Another contributing factor could be that the target movement, although similar to that used in Experiment 1A, was potentially more challenging without the support of a table, such that gravity had a larger potential to affect the movement and may have contributed to the fatigue that some participants experienced. The issue of fatigue is relatively common in stroke rehabilitation and de-weighting (i.e. removing gravity) using an easy to use home friendly device could be useful in future iterations to aid those participants with greater weakness. Two participants were excluded due to having excessive fatigue providing evidence that staff could not recommend the more challenging forward reach movement without a table to provide support as was used in Experiment 1A.

There are several limitations with Experiment 1B: First the virtual target uses the colours of red or green only, for those participants with issues such as colour blindness this could pose difficulties in perceiving accurate target reaching. Further, while in Experiment 1A, the end point of the target movement involved pressing a physical, tactile button, in contrast Experiment 1B involved a target in virtual space and therefore may have less ability to transfer into real world activities of daily living. Unlike the original version of *Sonic Sleeve*, which did not require a screen for participants to carry out the exercises, Experiment 1B relied on the virtual on-screen target for participants to see when the target was reached. With no tactile feedback to let the participant know the target had been reached there could be challenges to perceive the movement end point. Another limitation for both Experiment 1A and 1B is that the procedure relies on a therapist to spend time calibrating and setting up the system to each participant individually. This current approach would be hard to scale. With a larger data set machine learning could be used to automatically assess and place a participant into an appropriately challenging set of constraints to provide targeted feedback.

Another limitation is that the system once trained was calibrated to the current optimal movement patterns of the participant with no recalibration of the feedback thresholds possible when stroke participants were in the home. This inability to adjust feedback thresholds conflicts with the core principle of progression in rehabilitation, which requires maintaining optimal but achievable difficulty as patients improve motor capabilities and described by the Challenge Point Theory (Guadagnoll & Lee, 2004). This could be rectified by having the participant recalibrate at regular intervals with a therapist either in person or by providing a remote recalibration method. In future iterations an adaptive design could be useful where the thresholds for feedback could increase or reduce in difficulty automatically based on the current performance of the participant; alternatively, feedback thresholds could be adjusted manually by a therapist from the hospital via an online portal after reviewing a participants' task performance. This second approach would permit the therapist to retain full control over task difficulty and progress.

The data collected from the post-study questionnaires shows that participants were interested in new technologies to support their rehabilitation. All four participants rated high levels of enjoyment and thought that taking part was beneficial for their rehabilitation linking in well to recommendations laid out by (Chen et al., 2019). The fact that the majority of the participants required some technical support to gain access to video and Wi-Fi is not unusual and having technical support for sessions is a key recommendation in the Template for Intervention Description and Replication (TIDieR) checklist (Beare et al., 2021) where hundreds of participants attended over 3000 rehabilitation sessions online during the Covid-19 pandemic. As *Sonic Sleeve @ Home* was run with the researcher monitoring and guiding the participant through the research study access to the video link and Wi-Fi setup was the main technical challenge. However, that was resolved with the researcher via telephone with minimal impact to the participant. Once participants were online the Sonic Sleeve @ Home App was rated as very easy to use by all participants. All participants had enough space to use the App comfortably as recommended by (Li et al., 2021). Physiotherapists will often encourage a participant to work hard in a rehabilitation session building up intensity and repetitions hence the answers to Q12 about taking part being physically tiring was of interest with two participants stating they did find the exercises physically tiring.

The Rehab Kit was challenging to setup and shows a barrier to use with some participants being unable to setup the kit alone. Additionally, the noted issues with the HDMI cable and overall size of the device do pose specific challenges to anyone with an arm impairment. Another fifth participant was recruited for the study and could not take part as he was unable to connect the Rehab Kit to his TV due to the HDMI cable being too challenging with his impairment and having no family carer to support him.

A limitation of the post-study questionnaire was that it was designed specifically for this project, and standardised usability questionnaires were not used. While the results provide useful qualitative insights, they cannot be directly benchmarked against wider technology acceptance literature or compared to other rehabilitation system evaluations. Incorporating validated questionnaires like the System Usability Scale (Brooke, 1996), Intrinsic Motivation Inventory (McAuley et al., 1989), and Technology Acceptance Model (Hu et al., 1999) in future work would allow for more generalised comparisons between systems and user groups. The small sample of 4 participants is also a limitation. Further testing with larger more diverse groups would be needed to fully assess wider feasibility and acceptability.

Another issue noted in the research was that one song used for the study was not enough with participants requesting a longer playlist. Furthermore, the App was designed to run an experimental protocol to assess the effect of auditory feedback rather than create a full home-based exercise programme. A full programme would benefit from more variation and different targeted movements more aligned to personal goals and ADLs. However, despite these limitations all participants described participation as enjoyable, wanted to continue beyond the experimental session and reported that they would recommend it to others in need of similar rehabilitation. This is encouraging and with further development the Sonic Sleeve @ Home App could provide a far more varied set of exercises to encourage both high dose and optimal movements. The focus on movement quality using auditory feedback could be combined with other home-based technology interventions like M-MARK where activities of daily living (ADL) are the focus of the technology (Turk et al., 2022).

One participant suggested that the system could in future incorporate an adaptive component to ensure an appropriate challenge as advocated by Guadagnoll & Lee (2004). A commercial system would need to permit monitoring and tracking likely with a therapist web portal to ensure the system was working to an appropriate level for the participant and easily updated from clinic to home. This is corroborated when thinking about the care pathway from hospital to home — successful rehabilitation systems require adaptability to the participant needs and the environments where the technology is used (Martinez-Martin & Cazorla, 2019). Future iterations of *Sonic Sleeve @ Home* could run off a tablet with emerging technologies such as Google’s TensorFlow permitting motion tracking off smart phones at lower cost and greater portability that the Rehab Kit used in the current experiment. Additionally, pairing markerless tracking with other wearable options highlighted by (Wang et al., 2017a) would permit a participant to be tracked undertaking ADLs around the home rather than having to be seated in front of their home television.

Both experiments provide evidence that participants with chronic stroke can make use of real-time auditory feedback by increasing the proportion of time in optimal movement patterns. A key distinction highlighted by Schmidt & Lee (2019) as well as in the discussion of theoretical frameworks in Section 2.1.3 is the difference between motor performance and motor learning; performance represents temporary execution of a skill, whereas learning denotes relatively permanent capability over time (Schmidt & Lee, 2019). It is possible that some participants were able to leverage the concurrent auditory feedback to enhance performance by self-correcting posture during the experimental blocks. However, the brief protocol likely provided insufficient repetitions for significant motor learning to occur, as highlighted in animal models by Kleim et al. (1998) and Nudo et al. (1996) suggesting hundreds of daily practice trials are often required to drive cortical reorganisation underlying sustained capability gains.

Therefore, while auditory feedback may have allowed temporary compensation reductions during the blocks as a performance aid, lack of more permanent gains could signify challenges fully utilising the concurrent input to achieve motor learning (Schmidt & Lee, 2019). As Maier et al. (2019) emphasise true motor learning requires retention of improved capabilities over time, aligning with Krakauer's assertions that reductions in impairment require demonstrating generalisability versus context-specific performance gains (Krakauer, 2006).

The next chapter addresses whether the use of auditory feedback over an extended period of training can lead to retention effects, indicative of more permanent motor learning rather than transient performance gains. In other words, the goal is to assess whether participants can increase their time in optimal movement patterns even when the feedback is no longer present.

CHAPTER 6: LEARNING EFFECTS: REDUCING COMPENSATORY MOVEMENTS WITH AUDITORY FEEDBACK

6.1 Introduction

The two prior experiments in Chapter 5 provide evidence that real-time auditory feedback can reduce compensatory movements. A question that follows from these positive results is whether this real-time feedback can produce motor learning (i.e. that a participant with chronic stroke can learn to perform the movement with less compensatory movement, even when the feedback is no longer present). As the training blocks were short in Experiment 1A (50 repetitions with feedback) the dose was likely too low to see any motor learning take place. Animal models suggest that many hundreds of repetitions are required to elicit genuine motor learning (Nudo et al., 1996).

Two distinct types of motor learning have been defined: adaptation and skill learning (Huang & Krakauer, 2009; Shmuelof et al., 2012). Motor adaptation describes how the motor system responds to changes in the environment by adapting to new spatial goals (Kitago & Krakauer, 2013). If healthy participants are given reaching tasks where there is a mismatch between the position of a target and the perceived position, participants will adapt and learn to alter their movement based on error feedback reaching baseline within a single session (Lackner & DiZio, 2005). Skill learning, in contrast, can be defined as the ability to achieve a task such as learning to ride a bike or playing tennis where new patterns of muscle activation are required to achieve accurate task execution (Kitago & Krakauer, 2013). In skill learning there is a trade-off between the speed of task execution and the accuracy of task execution known as the speed-accuracy trade-off function (Shmuelof et al., 2012).

Feedback can modulate skill acquisition and improve the retention of motor learning (Kitago & Krakauer, 2013). There are two broad methods to provide feedback to participants; First, a knowledge of performance (KP) approach provides information about movement quality and kinematics. Concurrent KP provides real-time feedback during task execution, allowing individuals to immediately adjust their movements (Schmidt & Lee, 2019). In contrast, terminal KP provides feedback after a trial is completed, summarising performance to inform future attempts. Secondly, a knowledge of results (KR) approach provides outcome feedback at intervals following trials (Schmidt & Lee, 2019). The former approach and specifically concurrent KP is the feedback used in the current research permitting participants to correct their movements in real-time. This aligns with the literature emphasising the role of concurrent KP in supplying information about motor performance during a task to help individuals adjust their movements (Levin & Demers, 2021; Maier et al., 2019). Prior research has found that KP feedback can help encourage elbow extension and reduce compensatory movements (Cirstea et al., 2006; Cirstea & Levin, 2007) aligning with the goal to harness motor learning to maximise residual normal movement patterns in stroke rehabilitation (Krakauer & Carmichael, 2017).The distinction between concurrent and terminal feedback is important, as concurrent KP allows immediate adjustment, while terminal KP and KR guide future performance. Concurrent KP enables participants to problem-solve issues and refine quality of movement during the task; utilising KP during the task may lead to improved motor learning outcomes and a better retention of learned movement patterns when compared to KR (Maier et al., 2019).

Following on from the two experiments documented in Chapter 5 a second set of experiments were run (2A and 2B) to investigate whether a period of training with auditory feedback would reduce compensatory movements even when the auditory feedback is no longer present. This was achieved by comparing performance without feedback before and after a period of 200 training trials which included real-time feedback to guide optimal movement patterns. Experiment 2A reports on data collected in a clinical lab setting with only a single training block of 200 trials while Experiment 2B reports on an extended number of training blocks on consecutive days collected in the home environments of participants with chronic stroke. Both experiments aimed to address the following question: Can participants with chronic stroke who engage in a training session with auditory feedback for 200 repetitions learn to reduce compensation even when this feedback is no longer present? Demonstrating retention when the feedback is removed would indicate potential motor learning rather than transient performance gains dependent on the concurrent feedback.

6.2 Experiment 2A: Learning in the Lab

6.2.1 Aims

The primary aim of Experiment 2A was to assess whether a training period of 200 repetitions with auditory feedback results in reduced compensatory movements during a reaching task even when feedback is withdrawn, compared to a control group without feedback. This was assessed immediately after training (short-term retention) and 24 hours later (longer-term retention). Assessing retention after 24 hours addresses more permanent learnt capabilities rather than temporary performance gains (Schmidt & Lee, 2019). Same-day and next-day retention covers initial and longer-term retention while still allowing testing before potential detraining effects.

6.2.2 Methods

6.2.2.1 Study Design

The experiment used a between-subject repeated measures design with participants randomised into either an experimental group (with auditory feedback) or a control group (no auditory feedback). Randomisation was undertaken with the same online random generator as for Experiment 1A to assign participants to either group (experimental vs. control) based on their study ID number. A case-control study design was considered but not selected as the aim was to evaluate the effect of auditory feedback, requiring a control group of matched participants for comparison. The repeated measures element also allowed within-subject comparison of retention over time. A transfer test assessing performance on an untrained task was considered but not included due to participants being actively engaged in an intensive upper limb rehabilitation program. Including transfer tests under these conditions would not have effectively isolated the potential transfer effects solely to the intervention.

The order progressed from no feedback pre-training baseline, to feedback training, to post-training retention without feedback (see Figure 6-1). This controls for inter-subject variability by allowing within-subject comparison to the same individual's baseline performance without feedback. It also isolates the effect of feedback itself on retention by evaluating after removing the feedback stimulus. If feedback training preceded the no feedback pre-test, ordering effects could influence the pre-training baseline. There was at least one week washout period between Experiment 1A and Experiment 2A to further minimise the risk of latent learning on the pre-training baseline scores. Comparing retention to the pre-training baseline specifically assesses retention of feedback benefits over the participants' innate capabilities without feedback. Progressing from pre-training baseline to training to retention tests helps attribute any retention gains to the feedback training itself.

6.2.2.2 Participants

Participants from Experiment 1A who showed a significant effect of auditory feedback on the reduction of compensatory movements were invited to take part in the second Experiment 2A. Of the 14 eligible participants, four participants were excluded due to timetabling issues on the QSUL programme, and one participant was too fatigued to undertake the study on the day (see Figure 6-1). This left 9 participants who took part and completed the experiment. Table 6-1 shows the participant demographics, including scores on a range of clinical measures that are routinely assessed. Written informed consent was given by all participants and full ethical approval was attained by the London Dulwich research ethics committee (ref: REC 19/LO/0579) (see Appendix 5-3) with additional ethical clearance obtained from Goldsmiths University of London (see Appendix 5-4).

6.2.2.3 Procedure

A week after Experiment 1A was finished participants came back into the lab setting for Experiment 2A. As in Experiment 1A, participants performed seated forward reach movements while listening to self-chosen music. This time, however, there were 300 repetitions in total (compared with 100 in Experiment 1A). As in the first experiment there was a 10 second rest every 10 repetitions and a 2-minute rest every 50 repetitions. The control group completed all 300 repetitions without any feedback (self-chosen music continued regardless of quality of movement). The experimental group also received no feedback with the music continuing to play for the first 50 repetitions of the movement. Then they received auditory feedback (muting of the music when movement deviated into compensatory movement) for 200 repetitions during the training period followed by another block of 50 repetitions without feedback (short-term retention). 24 hours after this session participants

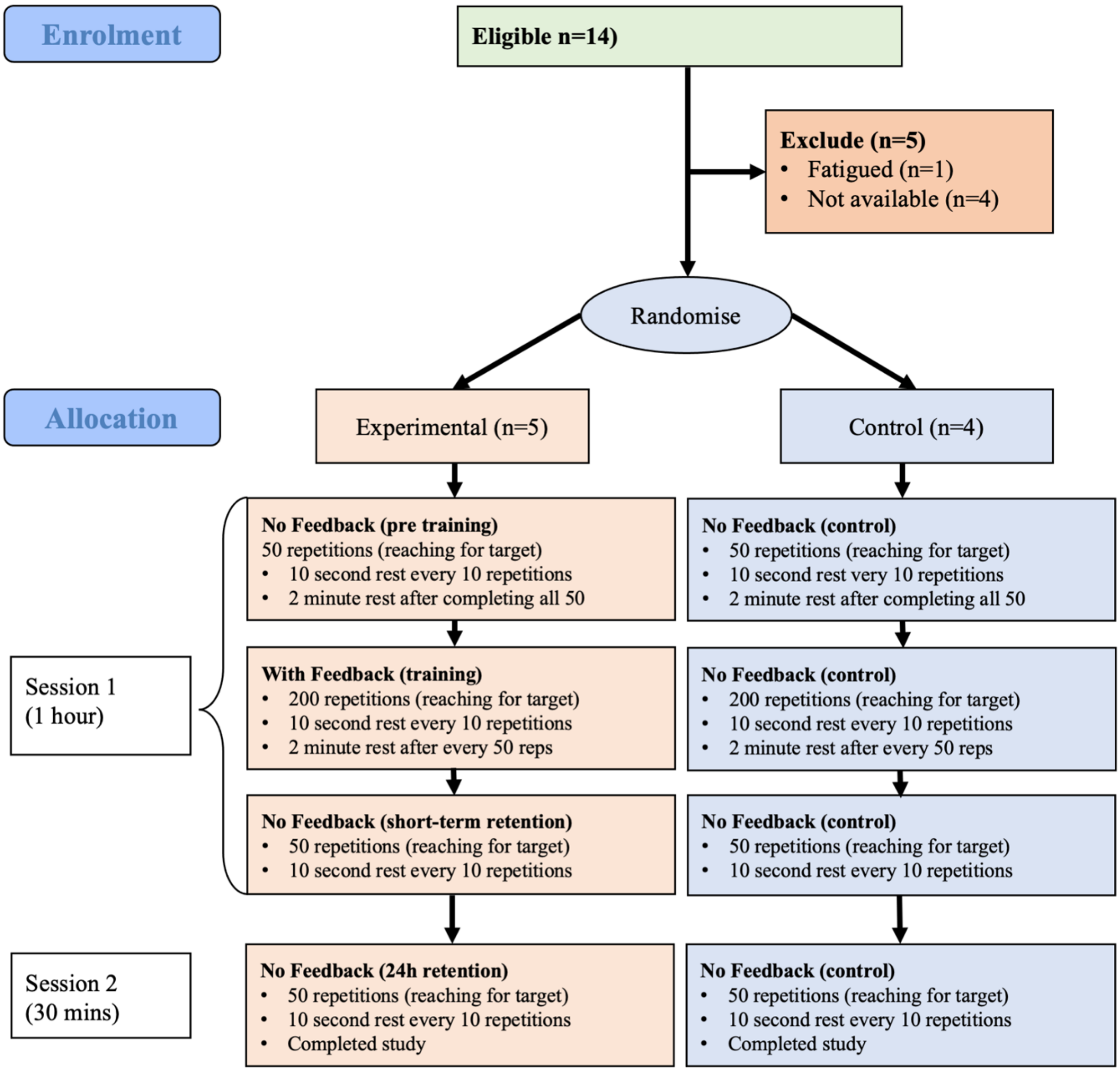

Figure 6-1: Flow diagram of participant progress through Experiment 2A.

Table 6-1 Demographic and clinical characteristics of patients in Experiment 2A

variable	With Feedback Group (n=5)	No Feedback Group (n=4)	*p*-value
Gender, male n (%)	4 (80%)	2 (50%)	.405
Age, median, (IQR), years	58 (44.5,68)	53 (27,59)	.556
Affected Limb, right n (%)	5 (100%)	3 (75%)	.444
Dominant Hand, right n (%)	4 (80%)	4 (100%)	1.000
Dominant Hand Affected, n (%)	4 (80%)	3 (75%)	1.000
Time Since Stroke, median, (IQR), months	26 (18.5,45)	17.5 (10.25, 107.25)	.556
Modified Rankin Scale, median (IQR), Max=5	3 (2.5, 3)	3 (2.5, 3)	.905
The Barthel Index, median (IQR), Max=20	18 (17.5, 19)	16.5 (16, 18.5)	.190
The Neurological Fatigue Index, median (IQR), Max=62	43 (39.5, 46)	38 (24, 38)	.143
Hospital Anxiety and Depression Scale, median (IQR), Max=34	9 (3.5,15)	22 (8, 22)	.250
Montreal Cognitive Assessment, median (IQR), Max=30	26 (19.5, 29.5)	29 (25, 29)	.571
Fugl-Meyor Sensory, median (IQR), Max=12	10 (10, 12)	10.5 (7.75, 11.75)	.730
Modified Fugl-Meyer (upper limb), median, (IQR), Max=57	29 18.5, 33)	21 (17.25, 36)	.905
Chedoke Arm and Hand Inventory, median, (IQR), Max=91	52 (31, 62)	50.5 (44.5, 61.75)	.730
Arm Activity Measure-A, median, (IQR), Max=28	6 (2, 7.5)	2.5 (1.25, 3.75)	.286
Arm Activity Measure-B, median, (IQR), Max=52	41 (23.5, 44)	38 (18.75, 46.75)	1.000
Apraxia, yes n (%)	0 (0%)	1 (25%)	.444

Difference in medians between groups were tested with Mann-Whitney U tests. Difference in proportions were tested with Fishers Exact Test. Significance of the tests are reported at .05 alpha level

completed a final short block of 50 repetitions assessing longer-term retention. As with Experiment 1A participants completed the St. Mary's Hospital Sleep Questionnaire before they started each session and at the end of each session participants rated their level of tiredness on the same 5 stage Likert scale as in the prior experiment.

6.2.2.4 Data Collection and Analysis

Data file outputs from the *Sonic Sleeve* system were processed in Python 3.7 (https://www.python.org) using JupyterLab (https://jupyter.org), and SPSS v24 was used to run the statistical tests. As in Experiment 1A, the dependent variable was the duration of compensatory movement as a proportion of total movement time. This was calculated for each movement repetition and then averaged across all 50 repetitions, for each condition. A two-way mixed ANOVA compared the dependent variable between groups with time as the within-subjects factor measured at three time points: pre training, post training and 24 hours post training. Follow-up paired t-tests were undertaken to explore differences in each group and Wilcoxon signed-rank tests were run to assess each participant's individual performance.

6.2.3 Results

Participant demographics and clinical characteristics were assessed (see Table 6-1). No significant differences in baseline characteristics were found between participants who received a period of 200 training repetitions with auditory feedback and those in the control group (Table 6-1). There was no statistically significant interaction between group and time on the duration of compensatory movement as a proportion of total movement time, *F*(1.346, 9.422) = 0.453, *p* = .574, partial η^2 = .061 (Figure 6-2).

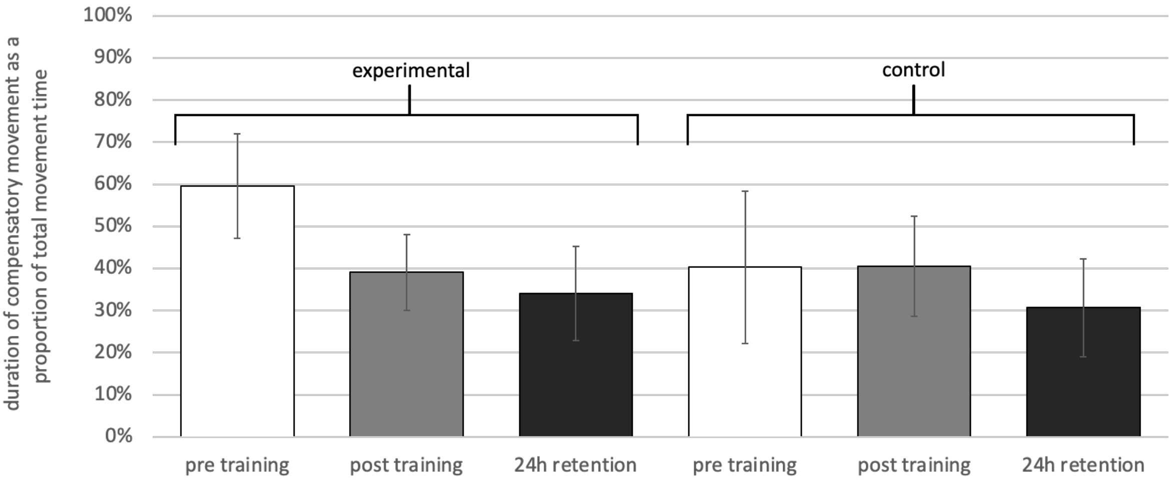

Figure 6-2: The duration of compensatory movement as a proportion of total movement time for 9 participants (5 experimental, 4 control) undertaking 50 repetitions in three conditions all without auditory feedback, pre training, post training (short-term retention) and 24hour retention.

Results from paired t-tests for all comparisons are shown in Table 6-2 below with no significance noted (*p*>.05). However, the experimental group shows a reduction in compensation during the post and 24-hour retention conditions (Figure 6-2) with a difference of over 21% on average between pre and the other two post training conditions. There is no such average change in the control group when comparing post training vs. pre training conditions and a 9% difference 24 hours later.

Table 6-2: *Descriptive statistics and results of paired t-tests comparing pre, post and 24 retention conditions in experimental and control groups*

Group	M (%)	SD	t(4)	*p*	95% CI		Cohen's d
					LL	UL	
Exp Pre	0.60	0.28					
Exp Post*	0.39	0.20	1.320	.257	-.227	.638	0.348
Exp 24h*	0.34	0.25	1.262	.276	-.307	.820	0.452
Exp Post vs 24h			0.542	.616	-.092	-.205	0.205
Con Pre	0.40	0.31					
Con Post*	0.40	0.11	-0.011	.992	.620	.616	0.388
Con 24h*	0.31	0.23	0.522	.638	-.490	.682	0.368
Con Post vs 24h			1.064	.365	-.196	.393	0.185

Note: M = mean duration of compensatory movement as a proportion of total movement time*, SD = standard deviation, t = test statistic of the independent samples t-test, p = probability value, CI = confidence interval, LL = lower limit, UL = upper limit; Exp = experimental group; Con = Control group; * = compared to pre scores within group.*

Individual level analyses showing the three conditions across groups, pre training, post training and 24hour retention highlight substantial variability (Figure 6-3). Three participants in the experimental condition spent significantly less time in compensation post training and 24 hours later. However, the results from the two other participants in the experimental condition and the four controls highlight mixed results that may explain the non-significant results in Table 6-2 above.

No participant reported any concerning issues with sleep based on a review of the sleep questionnaires suggesting that any lack of motor learning should not be attributed to sleep issues. All participants rated their tiredness after session 1 with 300 reps as more tiring than the second session with only 50 repetitions (Table 6-3). Individual groups assessed using exact sign tests were non-significant (p>.05), however, when pooling the groups to compare all 9 participants, the tiredness ratings were significantly higher after 300 reps compared to 50 reps.

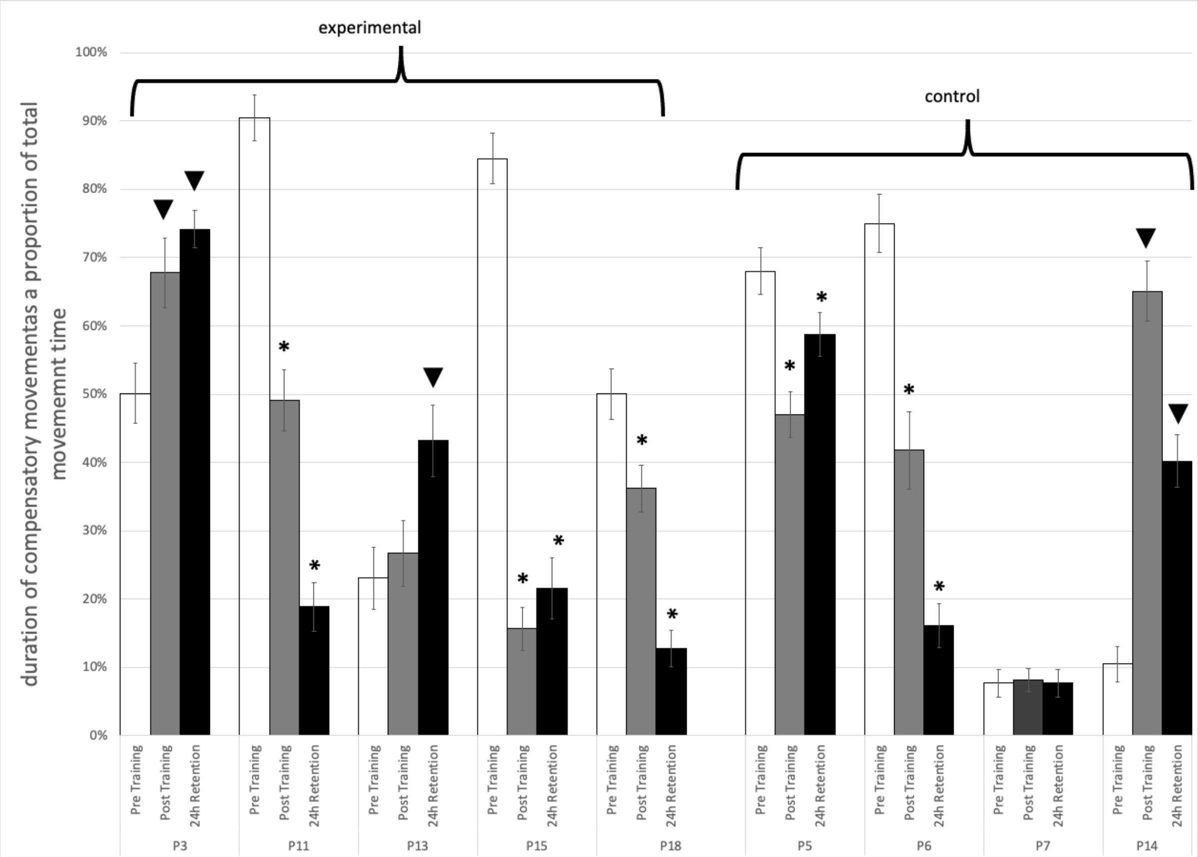

*Figure 6-3: Individual participant data showing the duration of compensatory movement as a proportion of total movement time for 9 participants (5 experimental, 4 control) undertaking 50 repetitions in three conditions all without auditory feedback, pre training, post training and 24hour retention. * = significant reduction in compensation compared to pre training; ▼ = significant increase in compensation compared to pre training.*

Table 6-3: Likert Tiredness Ratings Experiment 2A

Group	N	*Tiredness Rating Session 1 (300 reps)*	*Tiredness Rating Session 2 (50 reps)*	*p-value*
With Feedback, median (IQR)	5	2 (2, 2.5)	1 (1,1)	.074
No Feedback, median (IQR)	4	2.5 (1.25, 3)	1 (1,1.75)	.250
Combined	9	2 (2,3)	1 (1, 1)	.013

Note: Results from exact sign tests on Likert scale ratings of tiredness immediately after completing session 1 with 300 repetitions of the target movement and after session 2 with 50 repetitions. Pooled group results are also shown with all 9 participants assessed together.

6.2.4 Discussion

The current experiment investigated learning effects at two time points (short-term retention and 24hour retention) after a period of training with feedback. There was no significant difference between the experimental and control groups across three time points pre training, post training (short-term retention) and 24-hour retention. However, in the experimental group with 5 participants there was a trend suggesting some learning may have taken place at the group level with a mean reduction of time spent in compensation of over 20%; due to variability at the individual level this difference needs to be evaluated with caution.

The participant selection criteria focused on those showing performance gains with feedback during Experiment 1A. The rationale was that they may have the highest potential to exhibit motor learning effects that carry over post-training without feedback. However, as Schmidt & Lee (2019) describe, performance and learning are distinct. The substantial individual variability post-training may indicate some relied more heavily on the concurrent feedback for performance gains, while others transitioned to more permanent, retained learning. Additional screening approaches could help identify individuals most likely to show learning versus performance reliance based on feedback. Further exploring the variability between learning and performance effects seen here may help refine this process for future research. Evaluating the specific factors that predict retention of feedback could target those expected to respond positively to this type of training approach.

There are several reasons that may explain why learning was not evident at the group level in the experiment. First, the sample size was small (n=9) and could have masked any learning effects and there is a strong argument that the use of inferential statistics at such small group sizes is unlikely to provide any strong conclusions. However, reporting inferential statistics remains useful for communicating observations in familiar quantitative terms, while limiting conclusive claims. Effect sizes and variability provide indicative evidence on potential effects and uncertainty. Care is still needed interpreting the statistics descriptively rather than overstating conclusions. This early-stage proof-of-concept research warrants balanced use of available data to inform feasibility and guide further studies. Second, fatigue may also have masked learning in the short-term retention as evidenced by tiredness ratings being higher in the first session with 300 repetitions of the target movement. Finally, despite optimising movements with feedback the benefits may be lost when the feedback is removed due to an over dependency on the feedback as explained by the guidance hypothesis (Schmidt, 1991; Sigrist et al., 2013). This reliance on feedback can reduce learning post-training (Kitago & Krakauer, 2013) . However, there is some evidence that feedback in the auditory domain may not follow the guidance hypothesis principles; a study with 20 healthy participants (Fujii et al., 2016) found that extending the amount of real-time KP feedback elicited greater retention in learning both immediately after an acquisition phase and the following day (delayed retention). These findings suggest that auditory feedback may elicit motor learning in a more robust way than visual or haptic feedback, but more research is needed to verify this.

Despite the null results at the group level in this experiment the protocol can be extended to increase dose and vary the feedback to optimise the potential for learning. Several studies suggest that reducing feedback frequency over time increases learning (Goodwin et al., 2001; Winstein et al., 1994) and this could be incorporated in future research using a similar music-based approach. Music based feedback has been used in a number of studies but there is no consensus on what type of feedback may be most effective to promote motor learning.

While no significant group-level effects emerged, Experiment 2A provided outputs that suggest more research is warranted. The substantial individual differences observed highlight the need for larger sample sizes to better characterise response patterns and distributing practice over multiple days may mitigate this issue. Furthermore, the lack of a retention effect indicates more training is likely needed for learning consolidation, suggesting an insufficient dose from 200 repetitions with auditory feedback. Incorporating these insights, Experiment 2B implemented a distributed multi-session protocol over 2 weeks, providing a higher dosage of 2000 repetitions to determine if a dose-response relationship exists. Spreading practice over 10 separate days extended the intervention duration giving more opportunity for consolidation between sessions potentially leading to enhanced retention. While no significant effects emerged in Experiment 2A, the informative outcomes guided design refinements for further exploring the learning potential of auditory feedback training in the follow-up home-based Experiment 2B. The following sections describe the assessment of retention effects only this time in the home environment.

6.3 Experiment 2B: Learning in the Home

6.3.1 Aims

The primary aim of Experiment 2B was to assess whether a prolonged training protocol of 10 sessions with 200 repetitions of auditory feedback results in reduced compensatory movements during a reaching task when feedback is removed. This was evaluated on a within-subject basis by comparing compensation levels pre and post training for each session.

6.3.2 Methods

6.3.2.1 Study Design

The experiment used a within-subject single case study design. Participants taking part were allocated to 10 sessions repeating the same protocol on consecutive weekdays. There was a one-week delay between Experiment 1B and 2B to reduce the risk of latent learning for the initial pre-training baseline taken in Experiment 2B (see Figure 6-4),

6.3.2.2 Participants

Participants in the home who completed Experiment 1B and who showed a significant effect of auditory feedback on the reduction of compensatory movements were invited to take part in Experiment 2B. Of the 4 participants eligible 2 participants were not available (Figure 6-4). This left 2 participants who took part and completed Experiment 2B. Table 6-4 shows the participant demographics, including scores on a range of clinical measures that are routinely assessed. Written informed consent was given by all participants and full ethical approval was attained by the London Dulwich research ethics committee (ref: REC 19/LO/0579) as in Experiment 1B (see Appendix 5-7). The same Sonic Sleeve @ Home system running on the Evolv Rehab Kits (from the company *Evolv Rehab*™) was used to collect the data.

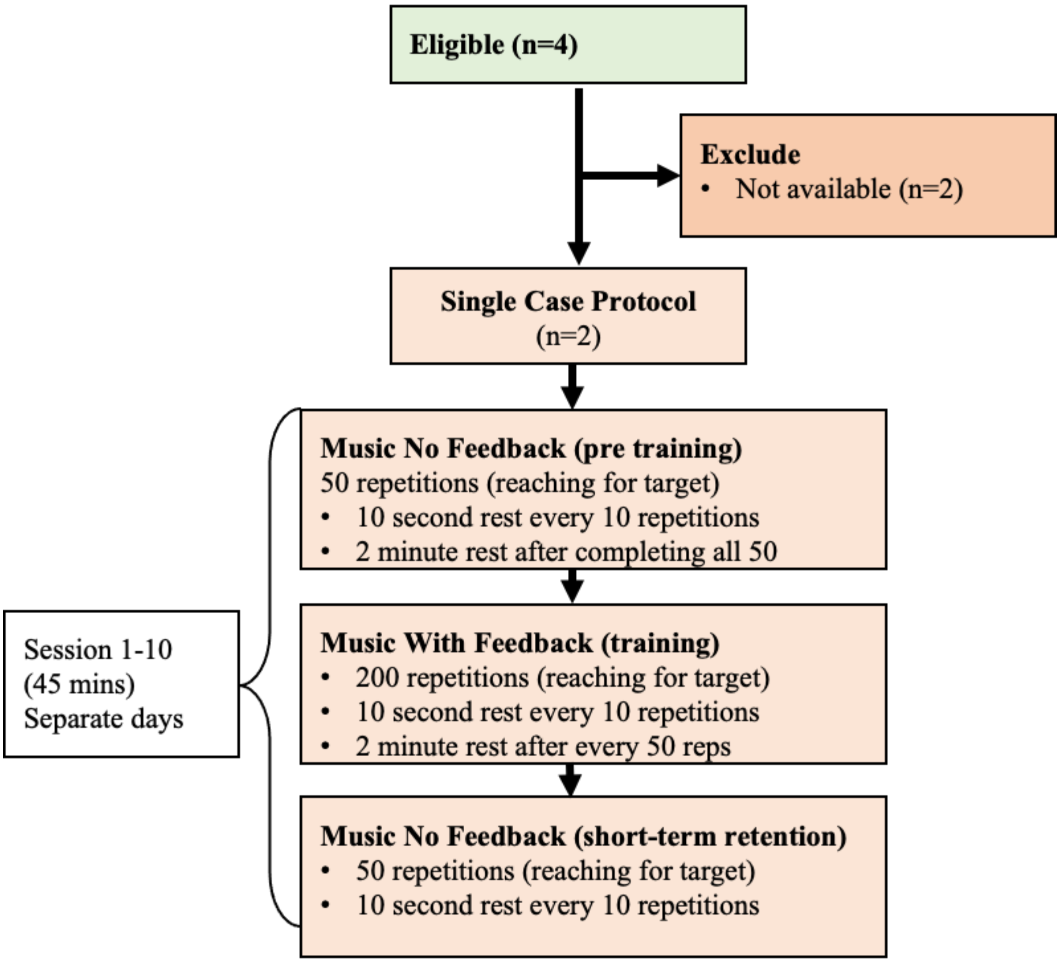

Figure 6-4: Flow diagram of participant progress through Experiment 2B

Table 6-4: *Demographic and clinical characteristics of 2 patients from Experiment 2B*

Patient ID (n=2)	Gender (M=50%)	Age (years)	AL (R=50%)	DH (R=50%)	TSS (months)	mRS Max=5	BI Max=20	FM-UL Max=54	Impairment Level	CAHAI Max=91	Arm-A Max=28	Arm-B Max=52	Apraxia (No=100%)
21	F	48	R	L	53	NA	18	51	mild	50	3	13	No
23	M	64	L	R	14	3	17	35	moderate	NA	0	28	No

Table 6-4 Abbreviations: AL = affected limb; DH = dominant hand; TSS = time since stroke; mRS = modified Rankin Scale; BI = Barthel Index; FM-UL = modified upper limb Fugl-Meyer; CAHAI = Chedoke Arm and Hand Activity Inventory; ArmA = Arm Activity Measure, na = data not available

6.3.2.3 Procedure

As soon as participants completed Experiment 1B they were invited to take part in the longer set of sessions for Experiment 2B. They had a one week break without training on the system as a washout period between Experiment 1B and 2B. The protocol was similar to that used in Experiment 2A (in the lab) but participants in 2B repeated the experiment 10 times, on consecutive weekdays undertaking 300 repetitions every day (total repetitions = 3000). Again, there was a 10 second rest every 10 repetitions and a 2-minute rest every 50 repetitions. Participants received no feedback for the first 50 repetitions of the movement. Then they received feedback for 200 repetitions during the training period followed by another block of 50 repetitions without feedback (immediate retention) (Figure 6-4). At the end of each session participants rated their level of tiredness on the 5 stage Likert scale as they had in the Experiment 1B.

6.3.2.4 Data Collection and Analysis

Data file outputs from the *Sonic Sleeve* system were processed in Python 3.7 (https://www.python.org) using JupyterLab (https://jupyter.org), and SPSS v24 was used to run the statistical tests. The dependent variable was the duration of compensatory movement as a proportion of total movement time. This was calculated for each movement repetition and then averaged across all 50 repetitions, for each condition either pre training or post training (short-term retention). Multiple Wilcoxon signed-rank tests were run to assess each participant across 10 sessions to compare the conditions, while controlling for familywise error rate. To mitigate the risk of making one or more Type I errors (false positives) when conducting multiple tests, Bonferroni correction was applied, setting an adjusted alpha level of 0.005 for each individual test.

6.3.3 Results

Participant demographics and clinical characteristics are summarised in Table 6-4. There was variability in the individual data as seen in Figure 6-5 and Figure 6-6 showing the two conditions (pre training and post training) across 10 sessions for both participants taking part respectively. The time spent in compensation was higher post training than pre training for the majority of sessions. Participant 1 (Figure 6-5) spent significantly more time in compensatory movement post training ($p < .001$) for session 1 through 9 while session 10 was nonsignificant. Participant 2 (Figure 6-6) spent significantly more time in compensatory movement post training ($p< .001$) for 8 sessions with session 9 significant ($p<.05$) and only session 8 showing no significant difference between conditions.

Exploration of training (200 reps with auditory feedback)

Considering that Experiment 2A showed a reduction in the duration of time in compensatory movement post training of around 20% it was somewhat surprising not to see evidence of this in the two participants studied in Experiment 2B where the data shows the opposite effect. To explore this inconsistency further, the data was broken down in a way that permitted visualisation of the 200 training trials broken into four 50 trial blocks. Participant 1 shows a distinct trend to increasing compensatory movement through the majority of blocks (Figure 6-7) while participant 2 appears to have very little compensatory movement in many of the blocks (Figure 6-8). Both participants rated their tiredness after all 10 sessions as not at all tiring. However, participant 1 had aphasia and it was not clear if they were underestimating their lack of tiredness. This is based on evidence from Experiment 1B when the participant rated the 100 rep sessions as stage 3 on the Likert scale “rather tiring” on a number of occasions as opposed to 1 “not at all tiring”. No adverse events were reported during the experiment or while on the QSUL programme.

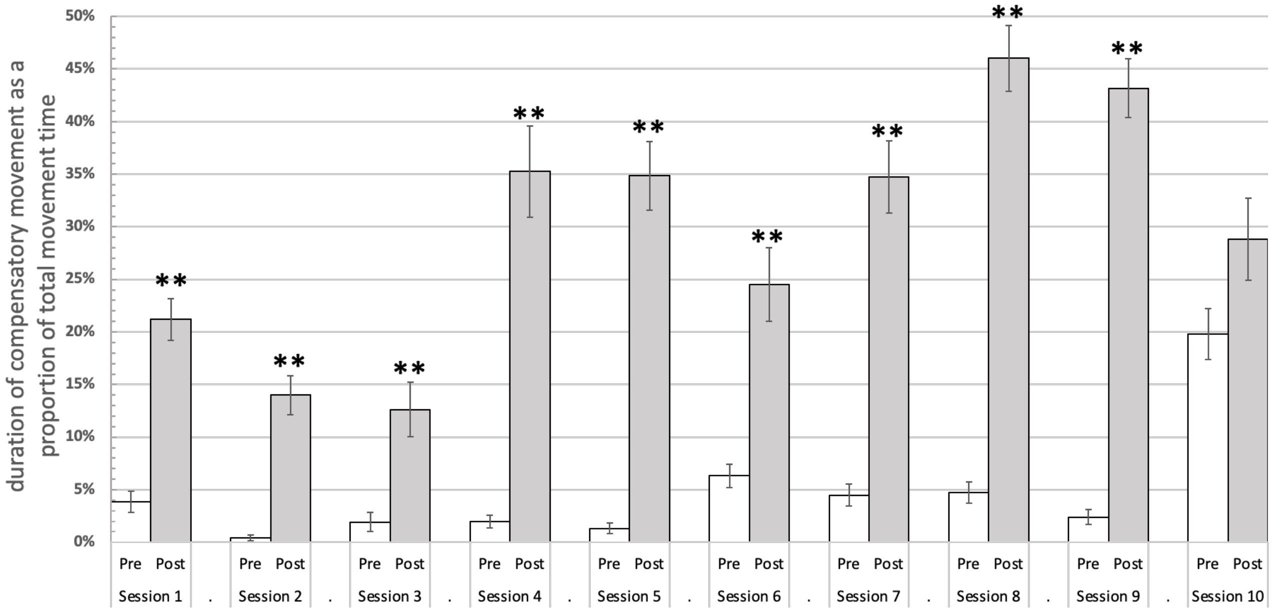

*Figure 6-5: Individual data for participant 1 showing the duration of compensatory movement as a proportion of total movement time undertaking 50 repetitions in two conditions, pre training and post training (short-term retention) over 10 sessions on consecutive weekdays. ** = significant difference (p < .001).*

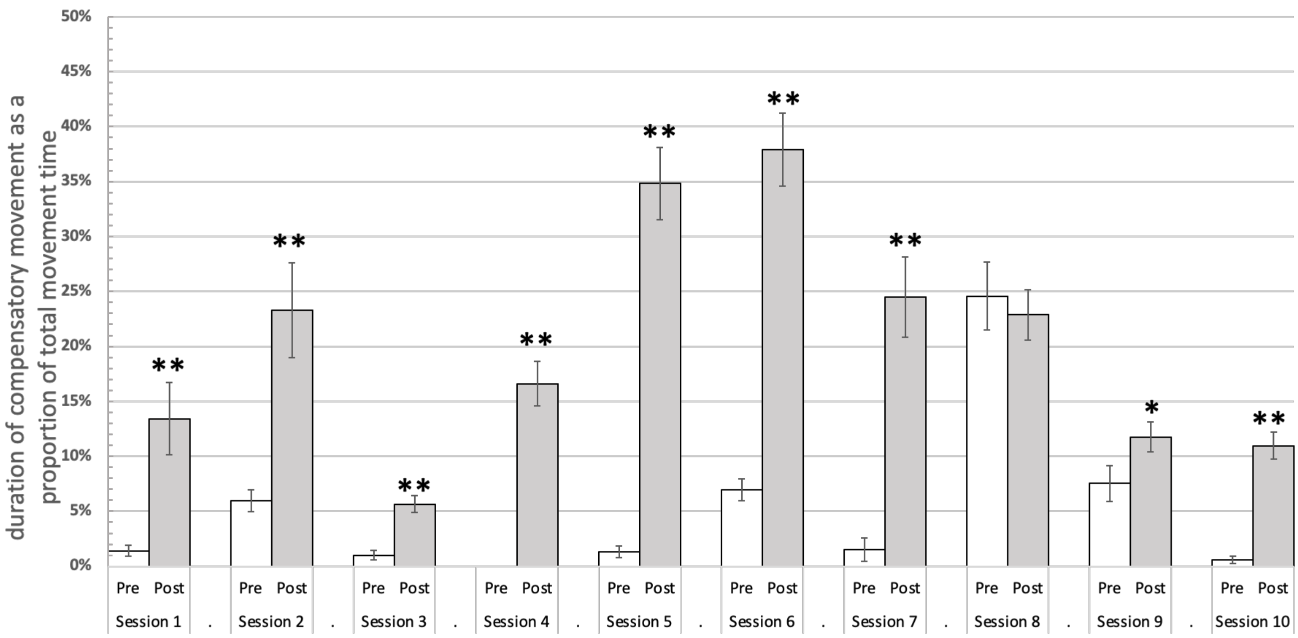

*Figure 6-6: Individual data for participant 2 showing the duration of compensatory movement as a proportion of total movement time undertaking 50 repetitions in two conditions, pre training and post training (short-term retention) over 10 sessions on consecutive weekdays. * non-significant difference using Bonferroni correction of .005 (p < .05); ** = significant difference (p < .001).*

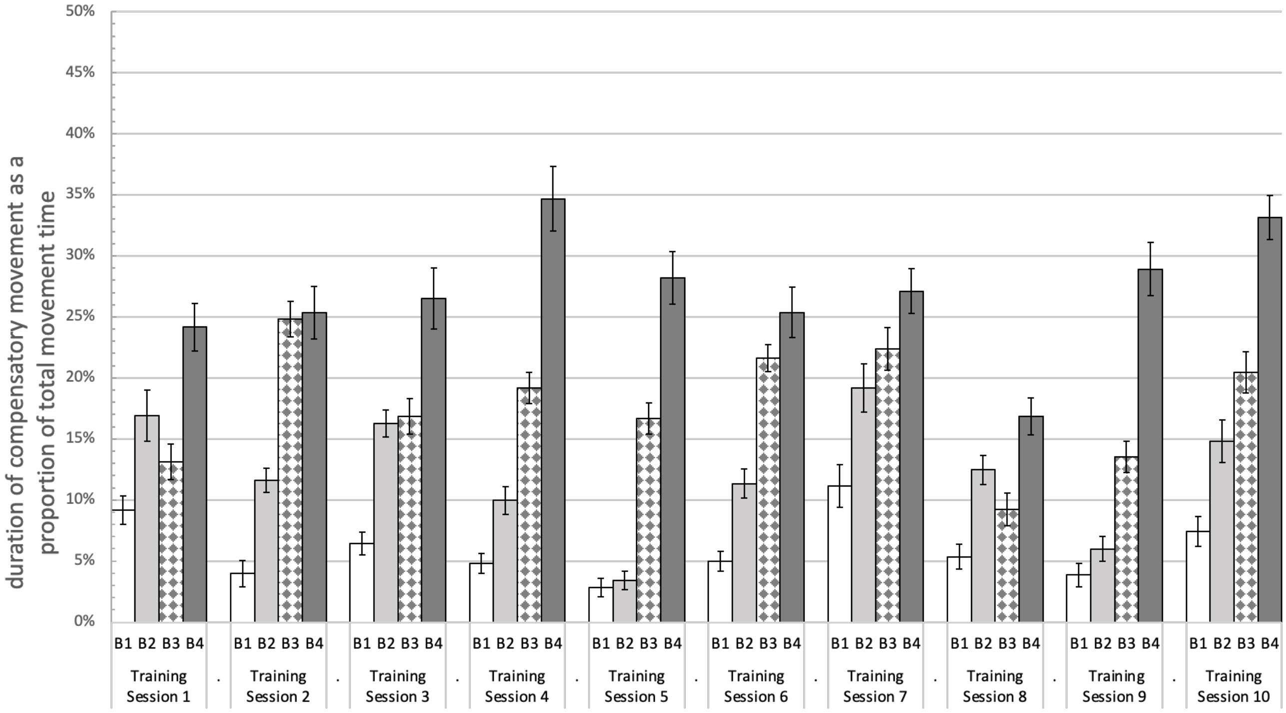

Figure 6-7: Individual data for participant 1 showing the duration of compensatory movement as a proportion of total movement time undertaking 200 training repetitions in 4 blocks of 50 over 10 sessions on consecutive weekdays.

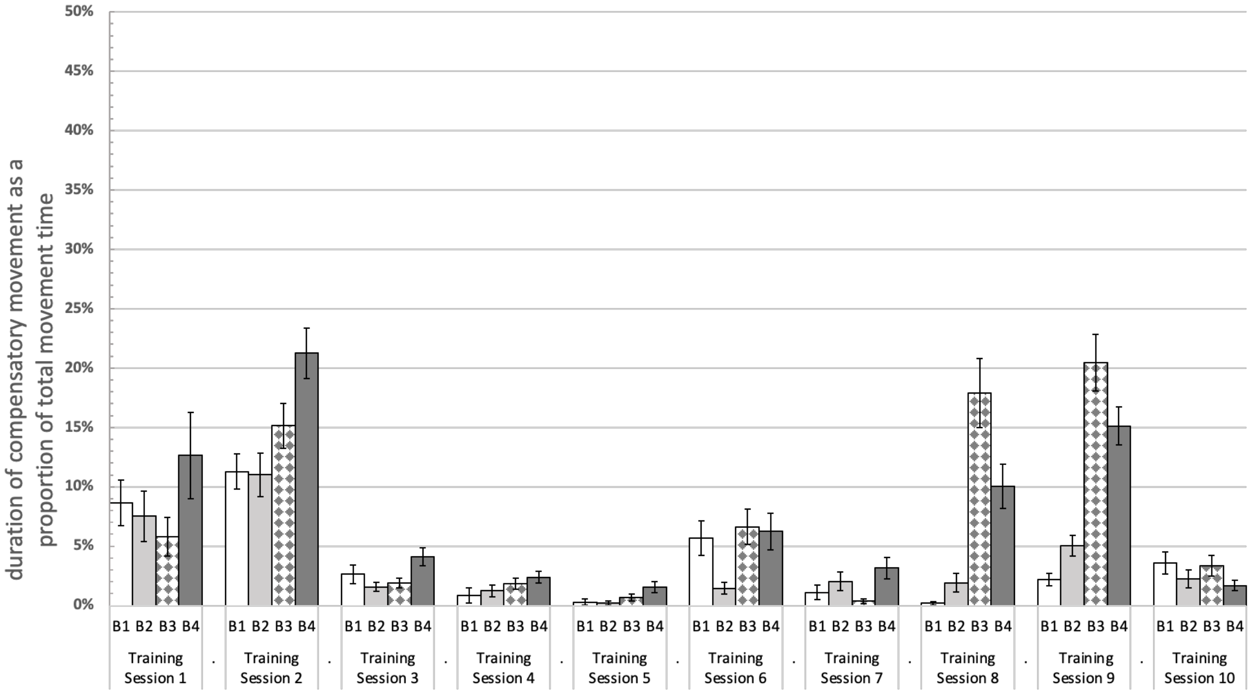

Figure 6-8: Individual data for participant 2 showing the duration of compensatory movement as a proportion of total movement time undertaking 200 training repetitions in 4 blocks of 50 over 10 sessions on consecutive weekdays.

6.3.4 Discussion

The current experiment investigated short-term learning effects after 200 trials of training with auditory feedback repeated over 10 sessions in the homes of two stroke participants. The protocol extended the number of sessions from Experiment 2A from one 300 repetition session to 10 totalling 3000 repetitions over two weeks. Surprisingly, in contrast to Experiment 2A, where at least some participants showed a reduction in compensatory movement even when auditory feedback was no longer present, Experiment 2B did not replicate this in the home environment. This lack of compensatory movement reduction was consistent for both participants across all 10 sessions run on consecutive weekdays so requires cautious evaluation. Both experiments had a small number of participants and therefore variability in the data was to be expected.

There are a number of reasons that may account for the differences: First that undertaking the task in the home although rated as not tiring was exerting for participants in some way that reduced their ability to learn during training. A second consideration is that the task was quite different between experiments with the virtual target in Experiment 2B requiring a different reaching task than the physical button target in Experiment 2A. Another key reason that may explain the results is that 200 repetitions of training may not be enough to elicit motor learning that carries over into a retention phase without feedback. It is unknown how long participants may need to train with Sonic Sleeve for motor learning to take place. The dose in the study of one session per day may not have been enough.

However, the overall 2000 repetition dose in the with feedback training blocks in Experiment 2B exceeded amounts eliciting retention in prior feedback-based training studies (Cirstea et al., 2006). This suggests other optimal dose considerations besides total repetitions likely apply for consolidating auditory feedback benefits, consistent with the challenge point framework where setting an appropriate challenge that matches an individual's rehabilitation trajectory is important (Guadagnoll & Lee, 2004). To keep the challenge at an appropriate level involves carefully tailoring feedback methodology, including type, timing, frequency and modulation over practice, for translation to meaningful learning outcomes rather than transient performance effects (Maier et al., 2019). Concurrent versus terminal schedules, along with fading of guidance over time, balance skill acquisition with retention and transfer (Winstein et al., 1994). In summary feedback delivery should align with each individual's changing needs over their evolving skill progression (Guadagnoll & Lee, 2004).

In this study, continuous concurrent feedback was provided throughout all repetitions in each training session. However, fading feedback frequency over the training sessions may have promoted greater transfer of possible feedback benefits. As participants came to rely on the constant real-time feedback guidance, their capacity to retain improvements without this support may have declined. Applying principles of reducing feedback guidance could strengthen deeper implicit learning promoting flexibility (Cirstea et al., 2006).

Given the consecutive daily training schedule in the current study it is worth considering longer term retention testing. Delayed retention evaluates participants’ ability to retain and apply acquired motor skills over the long term without continued auditory feedback (Maier et al., 2019). Rather than testing retention immediately after the last training session as in this study, allowing a longer interval before retesting would enable examination of whether improved compensation endures and transfers to real-world contexts (Schmidt & Lee, 2019).

Other possible reasons for masking a possible learning effect are evidenced in the data collected; Firstly, participant 2 was performing with very little time in compensatory movement suggesting floor effects that were particularly obvious in the 200 training trials. Secondly, within session fatigue seems a probable issue with participant 1 despite reporting low levels of tiredness post sessions. A clear pattern is seen where they tend to spend more time compensating as they progress through the session and are consistently spending more time compensating post training (short-term retention) than pre training despite having two minutes rest periods and rating their tiredness levels as “not at all tiring”. Furthermore, the one-week delay (washout period) between Experiment 1B and 2B did reduce the risk of latent learning for the initial pre-training baseline taken in Experiment 2B. However, participants did have three full sessions of training in Experiment 1B meaning there was more risk that they had carry-over learning that reduced any potential effect of auditory feedback. In addition, as the participants trained on consecutive weekdays for 10 days the risk of masking any potential learning effects as the sessions progressed is a concern.

Another potential issue with the *Sonic Sleeve @ Home* system is that due to relying on a television monitor and no physical target there is not a focus on activities of daily living (ADLs). In future iterations it would be recommended to extend the *Sonic Sleeve* approach to work in a more targeted way on ADLs. One home-based approach has been assessed for feasibility using sensors embedded into a garment and using knowledge of results (Turk et al., 2022). Participants were given feedback based on an avatar after attempting a range of ADLs common in stroke rehabilitation. As there is evidence that auditory based feedback may be particularly suitable for promoting motor learning with real-time KP feedback (Chen et al., 2016; Fujii et al., 2016) an interesting approach would be to combine the M-MARK and *Sonic Sleeve* approaches for home-based rehabilitation.

In conclusion, Experiments 2A and 2B assessed whether training with auditory feedback could produce retained reduction in compensatory movements, indicative of motor learning rather than transient performance gains. Experiment 2A provided tentative evidence that some participants may exhibit learning, with reduced compensation post-training that was retained 24 hours later. However, substantial individual variability was observed. In contrast, Experiment 2B did not demonstrate retention of feedback benefits, with participants in contrast increasing compensation post-training across sessions. While the lab-based approach suggested there was a potential learning effect for a subset of participants, the home system implementation was unable to elicit retention. Numerous factors around optimal dose, feedback delivery, task differences, and tracking limitations may explain variability in outcomes. Overall, the ability to fully utilise the real-time auditory feedback to achieve lasting changes remains unclear. Further research is needed to disambiguate these mixed results and better characterise those likely to show lasting versus temporary improvements using this approach. However, transient performance gains enabled by the feedback could still provide meaningful benefit if deployed alongside principles that promote longer term motor learning.

CHAPTER 7: GENERAL DISCUSSION

7.1 Introduction

The *Sonic Sleeve* research was a knowledge sharing endeavour and the results from the initial workshops, patient case series and subsequent lab and home-based experiments have highlighted the utility of real-time auditory feedback in aiding upper limb rehabilitation for stroke patients. However, the research as stated is couched as a proof of concept and requires further investigation and expansion to help fulfil the huge unmet needs of upper limb stroke rehabilitation. This chapter will provide a summary of the key findings from the *Sonic Sleeve* research in chronological order prior to focusing on the position of the research within the broader field of research and the implications and limitations of the research undertaken and described in this thesis. The final sections suggest directions for future research prior to a conclusion of this project.

7.2 Key Contributions

This proof-of-concept research makes three key contributions at the intersection of auditory feedback, machine learning, and stroke rehabilitation. First, it demonstrates compensation reductions across multiple compensatory movements using a low-cost, auditory feedback approach, expanding the narrow focus of most prior work on trunk flexion alone. Second, patient-selected music is incorporated as an inherent motivator enabling high repetitions, leveraging music's temporal structure, reward value and emotional attributes. Third, an interactive machine learning approach is introduced permitting clinician guidance to customise models, balancing human expertise with machine learning algorithms for more adaptive and personalised treatments. While requiring further research, this approach offers a foundation for next-generation stroke rehabilitation tools capable of enhancing both dose and movement quality during upper limb stroke rehabilitation.

7.3 Summary of Findings

There were a range of important outcomes from the feasibility workshops and case studies. The initial series of workshops provided good clinical oversight to ensure the scientific rationale for the research was sound and relevant for upper limb stroke rehabilitation. One key outcome was gaining an understanding that the intervention tasks did not have to be training a functional task directly – they could focus initially on impairment training. The final reaching task was designed to be most relevant to the widest selection of impairment levels leading towards function. Of note was the understanding that instructions needed to be explicit for stroke participants. The misunderstandings highlighted in the participant case studies led to the development of specific scripts that helped to guide stroke participants in the main experiments and helped participants to understand the task more clearly. The ambiguity when trialling various types of auditory feedback was an important finding leading to a decision to use binary feedback which supported broader inclusion criteria. Based on the expert feedback and combined with the iterative research and design on the stroke ward the justification to keep the auditory feedback as simple as possible while retaining the motivation of self-selected music was agreed to be most useful.

The current feasibility and experimental research in both lab and home settings provides evidence that auditory feedback is a promising tool for rehabilitation to help focus on movement quality without a therapist being present. In the initial Experiment 1A 14 participants were able to significantly reduce the duration of compensatory movement with a 20.1% reduction at the group level. Individual differences were seen with ceiling and floor effects evident illustrating the challenges of having rehabilitation systems successfully track participants with a broad range of impairments. Replication was evidenced for the four participants who undertook a similar paradigm in the home environment despite the task changing for the home-based version, where participants reached up to a virtual target displayed on a TV monitor rather than reaching for a physical button placed on a table. This home version was more physically demanding as without a table to support the hand and arm participants with severe impairment of the upper limb could not take part.

The focus of a second set of experiments was that of carry over effects after an extended period of training. Experiment 2A investigated learning effects at two time points (short-term retention and 24-hour retention) after 200 repetitions of the reaching task with auditory feedback. Despite results being non-significant there was evidence that learning may have taken place with a trend suggesting some reduction in compensation took place at the group level. However, with Experiment 2B where 2 stroke participants undertook multiple sessions of pre and post training in the home there was no such trend, and this could be attributed to the task being different (i.e., reaching up to a virtual target on a television screen rather than reaching on a table in the lab as in Experiment 2A). This was possibly an important difference but with such a small sample size it is hard to draw firm conclusions. A further possible reason why there was no positive effect in Experiment 2B (learning in the home) was that one participant had a mild impairment of the upper limb with floor effects and was likely not challenged by the task and therefore not benefiting from the feedback. The second participant did drift into compensation consistently over the 200 training reps implying that fatigue may have masked any possible learning that was taking place. However, despite the lack of evidence for learning the participants at home were able to achieve 300 reps per session over a period of 10 sessions and this dose was well tolerated as found in prior research where participants comfortably achieved over 300 repetitions on average per session (Birkenmeier et al., 2010). The two participants at home in Experiment 2B achieved well over 3000 repetitions illustrating a relatively high dose while reporting low levels of fatigue for all sessions. The findings suggest that the participants could have achieved an even higher dose. If the participants had worked into higher levels of physical exertion, they may have defaulted to more compensatory movements and therefore exposed themselves to higher levels of auditory feedback and potential for learning to take place.

It is interesting to hypothesise about what the key underlying mechanisms may be for the improvements seen in the initial experiments. Motivation is the most likely primary driver - if a participant compensates and the music is muted, they are motivated to get the music to play again as quickly as possible. When considering motivation, it is important to note participants could be motivated by visual, or haptic feedback as opposed to auditory. Furthermore, the auditory feedback could be effective using alarms and similar building blocks of sound rather than the self-selected music chosen for the final study design. There are other ways of tapping into the motivational aspects. It is important to realise that some people may not like music, and this was clear when one participant in the feasibility research, described in Chapter 4, stated they were not interested in music at all but may be interested in news, TV or audio books instead as the feedback modality. One size will likely never fit all for an intense high dose rehabilitation protocol. This leads to an important question: How can participants be motivated to do more over the longer term? This is a hard problem and one that has been approached by placing the participant at the heart of the rehabilitation process as the QSUL programme advocate, with education and personal goal setting deemed integral to long term adherence to rehabilitation programmes (Ward et al., 2019). By having patents take an active role in selecting the music they move to does put them at the centre of the decision making and provides an opportunity for a more active role in their rehabilitation.

7.4 Related Research and Theoretical Implications

Impairment Versus Functional Approaches

This research focuses directly on reducing compensation, aligning with impairment-based approaches which argue that promoting more normal motor patterns can lead to better long-term outcomes (Kitago & Krakauer, 2013). Compensation can exacerbate learned non-use and pain over time (Levin et al., 2009; Pain et al., 2015). Therefore, directly targeting compensatory movements may improve quality in the long run. While functional impacts were not directly measured here, prior evidence suggests that reducing compensation could improve movement efficiency and effectiveness over time (Krakauer, 2006; Levin et al., 2009). For example, an RCT by Michaelsen and colleagues (2006) found that restricting trunk motion led participants to use better elbow extension and joint coordination. Follow-up testing showed retained benefits 24 hours later. This indicates reducing compensation can have lasting impacts on movement quality. Hence, by focusing on minimising compensation, this aligns with an impairment approach, which Krakauer & Carmichael (2017) argue is needed to achieve true biological repair versus functional compensation strategies.

Achieved Dose and Intensity of Practice

The dose reached during experiments exceeds observed clinical practice, which averages just 32 daily upper limb repetitions (Lang et al., 2009). Instead, it aligns with intensive protocols showing 300 targeted repetitions are feasible (Birkenmeier et al., 2010) and can elicit clinically significant impairment reduction (Daly et al., 2019; McCabe et al., 2015). This highlights the motivational impact of patient-selected music in enabling increased intensity. Though below animal model targets of 400-600 repetitions (Kleim et al., 1998; Nudo et al., 1996), the current dose achieved compares favourably to constraints of inpatient settings that limit intensity (Krakauer & Carmichael, 2017). Music's inherent temporal structure can drive rhythmic movement, while the reward value engages patients (Särkämö et al., 2008). The *Sonic Sleeve* approach leverages music's motivational qualities to approach intensities matched to neuroplasticity thresholds established in animal models. It also meets calls for greater dose in stroke rehabilitation (Pollock et al., 2014). Though more research on optimal quantities is warranted, the achieved repetitions enabled intensive practice.

Participatory Design

The participatory design approach used in the current research aligns with calls to involve diverse stakeholders, especially patients, to enhance adoption of new rehab technologies (Palmer et al., 2019). The interactive workshops enabled clinicians to feed directly into system design ensuring clinical guidance on decisions while service user case studies allowed rapid refinement of prototypes based on capabilities and preferences ensuring a user-centred design. This human-centred approach balances clinical applicability with real-world validation through service user participation. Similar co-design methodologies have shown benefits for creating customised, patient-centric stroke interventions with better adoption (Dobe et al., 2023; Driver et al., 2020). Hence, the research methodology allowed clinical relevance and patient perspectives to jointly guide system development. Tight feedback loops enabled swift optimisation based on user needs. This approach matches recommendations for participatory design in rehabilitation technology (Farao et al., 2020).

Auditory Feedback

Unlike prior work narrowly targeting trunk compensation (Thielman, 2010; Thielman & Bonsall, 2012), this research introduced concurrent auditory feedback on multiple compensatory movement patterns including shoulder abduction and shoulder elevation. Expanding compensation monitoring aligns with recommendations from a recent systematic review (Wang et al., 2022). The current project builds upon research by (Valdés & Van der Loos, 2018) using multimodal augmented feedback including visual, vibrotactile and auditory components to reduce trunk compensation. However, their system was complex, costly and not as readily translatable outside the clinic. The current work offers a simplified auditory approach harnessing patient-selected music as a motivator that can transfer into the home environment at low cost. The auditory feedback gave concurrent Knowledge of Performance (KP), providing real-time information about quality and coordination of movements during task execution important for skill acquisition (Schmidt & Lee, 2019). This allows individuals to adjust their posture while performing exercises, optimising movement in real-time. Further, the self-selected music was incorporated to motivate practice based on the author and colleagues prior research (Kirk et al., 2016) and based on the reward value of music to enhance recovery and mood (Särkämö et al., 2008).

Interactive Machine Learning

Interactive machine learning (IML) permitted clinician guidance of algorithms toward customised treatments adaptable to individuals as recommended by Lee et al. (2020). This is an example of human-centred AI approaches (Shneiderman, 2022) which have been highlighted as instrumental in intelligent systems for rehabilitation. The methodology combined clinician expertise with data-driven optimisation toward more patient-centric treatments that align with increasingly personalised stroke interventions as recently reviewed by Choo & Chang 2022).

In summary, this research intersects with several key areas in technology-enabled stroke rehabilitation, contributing a uniquely integrated approach. Combining auditory feedback, patient-selected music and interactive machine learning under a participatory research and design methodology offers a novel paradigm. The approach helped to develop a customisable platform to target two key factors underlying effective rehabilitation: dose and movement quality. While limitations exist, the results warrant further investigation.

7.5 Limitations

There are a number of limitations to the current research. Firstly, due to a low sample size no firm conclusions can be drawn. The small number of participants (n=4) who saw replication in the home is a promising step but far more research in this area is warranted to ensure this effect is robust. Floor and ceiling effects caused some issues in understanding why participants may not respond well to the intervention and none of the 14 clinical baseline variables were found to predict those participants who did not make use of the auditory feedback.

Both the lab and home versions of *Sonic Sleeve* only had one designated target position and therefore did not lend itself to more variable movements that are recommended (Resnik & Jensen, 2003). One way to ensure more variability would be to permit a selection of varied tempo in a longer playlist. Using only one self-selected favourite song was not enough as stated by the participants who undertook the at home study. It is clear that motivation may reduce over time with such a limited playlist and the participants' enjoyment could even turn into disliking over a longer period of time. Maintaining participant satisfaction over time needs to be considered with any music embedded in rehabilitation technologies that aim for high dose where many hours of rehabilitation are recommended.

A notable limitation of the study was the absence of tiredness assessments after each experimental block. The current research protocol failed to collect data on participants' levels of tiredness following individual conditions, opting instead for a single report after both conditions were completed. This approach prevented a comprehensive analysis of the influence of each condition on participants' tiredness.

A technical limitation of the current system was the fact it had to be individualised to each participant and required a therapist to set the thresholds of feedback. This means that the system cannot generalise and scale up to suit many other participants without the individualised training. Over time with a larger number of participants there is a chance this could be resolved with the use of templates or machine learning to assess and categorise a participant automatically and additionally use adaptive thresholding to increase or reduce difficulty based on participant performance. The integration of adaptive thresholding mechanisms would align with appropriate challenge for participants as advocated by Brown et al. (2016) and Guadagnoll & Lee (2004) and could prove to be instrumental in dynamically adjusting task difficulty based on participant performance, thereby reducing the need for manual adjustments.

Another key limitation in the lab-based study was that the initial version with a single webcam using OpenPose used 2D kinematic data meaning that trunk flexion was challenging to track. The use of cameras at the 2 or 10 o'clock positions depending on the affected limb did permit tracking of trunk flexion, however, the movement tracking approach was likely not as optimal as a 3D motion capture system. Benchmark testing to compare *Sonic Sleeve* to motion capture systems could have been carried out with healthy participants to extend on the subjective tests that were carried out. Further issues were found with the *Sonic Sleeve @ Home* App version that had some stability issues with the unity Windows 10 crashing a number of times. However, it is important to note that the crashes never happened during the experiments.

The use of binary feedback in the current set of experiments may be too limiting for a more experienced participant who would benefit from greater challenge. There is a case that layering sounds may be more enjoyable than the simple binary feedback for more advanced users. An additional limitation of the current approach is that the system did not allow for the analysis of other variables of interest such as smoothness and accuracy of movements. Furthermore, the current technology was not setup up to be able to assess the periodicity of the music to see if this may be responsible for any of the benefits. This meant there was no way to assess if participants who benefit the most from the feedback were also the ones who entrained most closely to the tempo of the music. This is an interesting research direction for future iterations of the system. The primary aim of the system was to encourage better quality movement by reducing compensatory movements not enforcing entrainment to the music.

The current study encompasses various facets of skill acquisition, each warranting individual consideration within the context of motor learning in stroke rehabilitation. Firstly. both explicit and implicit learning are fundamental components of motor skill acquisition (Schmidt & Lee, 2019). Explicit learning involves conscious, deliberate efforts in planning and executing movements, while implicit learning relies on non-conscious, automated processes refined through practice (Schmidt & Lee, 2019). The current research employed three distinct compensation methods but offered only one feedback signal, which was muting the music. This design aspect forced participants to engage in exploratory problem-solving, a process with implications for potential implicit motor skill acquisition (Levin & Demers, 2021). This situation raises the possibility that implicit motor strategies, operating beneath conscious awareness, may have played a role (Krakauer, 2006).

Feedback, particularly the concurrent Knowledge of Performance (KP) as used in this research, plays a critical role in motor learning, aiding in error detection, correction, and the optimisation of motor skills (Schmidt & Lee, 2019). Lastly, the null results obtained in Experiment 2A and 2B, where short-term retention was assessed after 200 repetitions of training, should be considered within the broader framework of motor learning principles. According to Krakauer (2006), understanding the influence of rest periods and introducing variation in practice intervals is crucial for detecting significant retention of learning. Rest periods facilitate the consolidation of motor learning, contributing to long-term retention and skill acquisition (Schmidt & Lee, 2019). In summary, the study encompasses various facets of skill acquisition, including explicit and implicit learning, the role of feedback in problem-solving, and the importance of rest periods and variability in practice intervals. However, none of these skill learning aspects were tested systematically and would require further research to unpack.

Furthermore, when aiming to optimise movements with feedback the benefits may be lost when the feedback is removed due to an over dependency on the feedback as explained by the guidance hypothesis (Schmidt, 1991; Sigrist et al., 2013). This reliance on feedback can reduce learning post-training (Kitago & Krakauer, 2013). The key issue is that participants may become dependent on the feedback making task performance worse post training when the feedback is no longer present. This assertion is important to consider as in the current thesis research the auditory feedback (muting of ongoing music) was available continuously in the experimental condition for participants to utilise. There is some evidence that permitting continuous auditory feedback, as is the case for the experimental conditions in the current thesis, may provide retention of motor learning, without manipulating and reducing the feedback. KP auditory feedback has been found to elicit better skill retention with more rather than less auditory feedback in healthy participants (Fujii et al., 2016) that appears to contradict the guidance hypotheses. It could be that auditory feedback improves skill learning when providing continuous access to feedback, there is a need for more research to understand the implications and apply them in clinical settings.

7.6 Future Directions

There are a few distinct ways that *Sonic Sleeve* could be extended in future research from a number of levels. One of the most obvious is to extend the target movements to include a range of vertical and horizontal reaching targets. Another consideration is aiming to improve the feedback applicability for long term rehabilitation by making *Sonic Sleeve* adaptive and permitting the system to consistently work to a participants' current abilities; the task challenge could be kept to an individualised adaptive level ensuring participants are continually challenged and continue to progress towards better quality more efficient movement patterns. A further extension to the current study would be to systematically reduce the feedback over time to see if this approach would elicit enhanced learning as described by the guidance hypothesis (Goodwin et al., 2001; Winstein et al., 1994)

There are several questions not addressed in the current research. First, a key question to be addressed is can interventions using auditory feedback transfer into daily life? More specifically, does moving the kinematics of a stroke participant's movement, to become more "normal", have an impact on their quality-of-life? Another question not addressed in the current study is: What should the dose be? As highlighted in the recent Cochrane review (Clark et al., 2021) understanding the dose of upper limb rehabilitation is challenging. It is unclear how much training is required to increase the movement efficiency for longer periods. It could be argued that the auditory feedback used with *Sonic Sleeve* is somewhat comparable to what a therapist may do in providing feedback to help guide a participant into optimum movements. However, a future study could assess the difference between therapist and auditory feedback and see if there was a comparable correction of poor movement patterns between feedback types where an analysis for equivalence could be undertaken. Systems such as *Sonic Sleeve* could track participant progress and permit virtual monitoring saving therapists and participants unneeded costly travel time and reduce face-to-face time while maintaining a high level of rehabilitation.

Another key consideration is assessing the feasibility of undertaking this approach in the acute phase of stroke. If service users can focus on movement quality and high dose in the early phases of rehabilitation, there may be a significant opportunity to improve their quality of life at a faster rate. There is some evidence that there may be an opportunity for enhanced rehabilitation in a short window during the first month of stroke where motor control can be a key focus of rehabilitation and essential for more complex motor tasks of the upper limb (Cortes et al., 2017).

An interesting way to expand on the system would be to assess how closely participants entrain to the beat of the music. However, the data collected illustrated a clear trend that when participants receive the auditory feedback they tend to slow down and are therefore possibly less in sync with the tempo of the music. In other words, the participants who are the most uncoupled from the sound may see the most reduction in compensatory movements. There is likely a trade-off between the benefits of entrainment (which was not enforced in the current research) and the ability for a participant to slow down and problem-solve their way out of poor-quality movement patterns and into high quality movements. Further suggestions for extending *Sonic Sleeve* include incorporating the ability to capture and measure smoothness and accuracy and precision of movement and feed these data back to participants to review their progress and furthermore, to permit therapists to track improvements in movement quality over time.

7.7 Conclusions

The current research has broad implications for stroke rehabilitation particularly in the home environment where most rehabilitation takes place and where a therapist is rarely present. The *Sonic Sleeve* proof of concept system shows that real-time auditory feedback on multiple compensatory strategies beyond that of trunk flexion can help participants reduce the proportion of time they spend in compensatory movements. There are three key strengths to the auditory feedback approach. First, music has strong links to the pleasure and reward circuits (Blood & Zatorre, 2001) – self-selected music taps into our emotions and can motivate movement. Secondly, music with the presence of a beat lends itself to high dose – by entraining to the beat a high number of repetitions can be achieved. Thirdly, music is a multidimensional signal that can be manipulated in many ways. For example, various features of the sound can be mapped to signal different types of compensation by using pitch, speed, and volume as was trialled with participants in the case series discussed in Chapter 4. Additionally, auditory signals allow participants to focus on specific tasks away from a digital screen. This approach is arguably more representative of real-world activities such as cooking, cleaning, and washing and auditory feedback could be applied directly to these ADLs. The use of self-chosen favourite music provides a motivational paradigm with prior research suggesting that even unfamiliar music if liked by participants may elicit strong positive emotions with activations of the limbic and paralimbic systems (Brown et al., 2004). Playlists of songs that are liked by participants can tap into their emotions and encourage participants to achieve a high number of repetitions as in prior research (Kirk et al., 2016). The tempo of the music can also provide a framework to encourage movement at a range of tempi encouraging variation of movement speed.

The current research suggests that real-time auditory feedback can be an effective way to help stroke participants reduce the proportion of time they spend resorting to poor quality movements. With further adaptation the approach illustrated and evaluated using *Sonic Sleeve* could be incorporated in any number of rehabilitation technologies. Providing movement parameters are being captured from either camera based or sensor-based devices the movements can be mapped onto real-time auditory feedback that encourages more consistent high quality movement adaptations.

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Appendix 3-1 System Trials

TRIAL N	Aim	Pre-processing (transform smoothing)	ML Approach	Constraints	Algorithm	Sonification	Rating out of 10	Notes
1 Camera to the right hand side. 25th April 2018	Simple test using Wekinator template. Forward reach right arm only 2 poses	None: Raw data only	Continuous Input: 12 features Models: 3 continuous	Outputs soft limit between 0 and 1 default no other constraints. This meant it could go out of bounds.	NN with 1 hidden layer. Trained on all 12 features in the same way.	Not undertaken as pd needed reinstalling.	5. The models were not differentiated so no point in having 3 continuous outputs. Tracked 2 poses 50% accuracy	This was a first attempt and more trials were required. Decided to use simpler classifiers next trial.
2 Camera to the right hand side. 21st May 2018	Forward reach right arm only 2 poses	None: Raw data only	Classification Input: 12 features Models: 1 output 2 classes	Output classes to give either number 1 or 2. No other constraints.	AdaBoost.M1 with 100 training rounds as default. Base Classifier: Decision Tree	Not undertaken as pd needed reinstalling.	7 This was one model tracking 2 poses. It did this quite well approx 70% accuracy in pose 1 vs 2..	The numbers were consistent most of the time. Seemed to deal with noise more than the NN
3 Camera to right hand side. 25th May 2018	Forward reach right arm only 2 poses for positive feedback. 2 over-comp poses (elbow out and lean forward). Map to sounds.	None: Raw data only	Classification Input: 12 features Models: 1 output 4 classes	Output classes to give either number 1, 2, 3 or 4. No other constraints.	K-Nearest Neighbors Trained on all 12 features N of neighbours 1	Triggered simple samples in pd using a timing mechanism. Triggered kick and snare for positive and chimes for negative	3. The model was not working very well. A lot of error. Tracked 4 poses at around 30% accuracy - possibly due to lighting conditions	Should try adding in 3rd compensation (shoulder lift) and go back to AdaBoost rather than K nearest neighbour?
4 Camera to right hand side. 5th June 2018	Forward reach right arm only 2 poses for positive feedback. 3 over-comp poses (elbow out, trunk lean and shoulder up). Map to sounds	None: Raw data only	Classification Input: 12 features Models: 1 output 5 classes	Output classes to give either number 1, 2, 3, 4 or 5. No other constraints.	AdaBoost.M1 with 100 training rounds as default. Base Classifier: Decision Tree	Triggered simple samples in pd using a timing mechanism. Triggered kick and snare for positive and chimes for negative	7. The model was working quite well. Tracked 5 poses at around 70% accuracy.	Created a video to share with team. It was a good start despite there being no noise reduction
5 Camera to right hand side. 5th June 2018	Forward reach right arm only: one continuous movement trained. Aiming to permit a musical scale 8 notes to be triggered.	None: Raw data only	Continuous Input: 12 features Models: 1 continuous	Output float: soft limit between 0 and 1 default no other constraints. This meant it could go out of bounds.	Linear Regression with no feature selection as default.	Triggered 3 samples at 0, 0.5 and 1. Did not preogress onto 8 full sounds and only triggered percussion sounds.	3. The model did not work very well. Tracked 3 stages of forward reach exercise. Signal noisy.	Need to clean the data to improve this strategy.
6 Camera to right hand	Build a seperate Weki patch for compensation	None: Raw data only	Classification Input: 12 features	Output classes to give either number 1,	AdaBoost.M1 with 100 training	Not relevant for this stage.	This was not to test a new model but to	Use one weki project for positive

side. 6th June 2018	alone and test 2 OSC channels		Models: 1 output 3 classes	2, or 3. No other constraints.	rounds as default. Base Classifier: Decision Tree		test using 2 weki projects. This worked fine.	sonification (port 6448) and one project for negative (port 6449)
7 Camera to right hand side. 7th June 2018	Try using NN again on Mick's advice. Forward reach right arm only to track 2 poses.	Data smoothed in PD after training in Weki 100 samples. Use pack and line objects.	Input: 12 features Models: 1 continuous	Outputs soft limit between 0 and 1 default no other constraints. This meant it could go out of bounds.	NN: 3 hidden layers. Trained on 12 features initially.	Triggered the same samples as above (kick, snare). Used pd **change** object method to trigger sounds.	6 Model was quite noisy. Worked with around 60% accuracy for tracking 2 poses.	Not sure that the smoothing is working very well. Look into smoothing before training the model.
8 Camera in front 14th June 2018	Track Hand-to-mouth via 3 poses and aim to get a NN working more effectively by training more carefully with a camera in front. This will allow bimanual movements if needed.	Data relative in pd (subtract neck x,y,z pos) then smoothed using a window size in WekiHelper - size 20.	Input: 9 features (remove neck position as this is not deemed important) Models: 1 continuous with 3 poses at 0, 0.5 and 1	Output float hard limit between 0.0 and 1.0	NN: 3 hidden layers. Trained on 12 features initially then reduced to 9 and 6 to improve speed.	Triggered the same samples as above (kick, snare) with addition of high-hat for mouth position.	7 Model was working ok: However, occasional swift slips from pose 3(mouth) to pose 1(table edge). This is not good and needs resolving.	Try using separate models for each pose as a lot of extra training examples appear to be needed. Even then accuracy is not as high as I would like
9 Camera in front 14th June 2018	Track compensation 3 poses and aim to get a NN working more effectively by training more carefully with a camera in front.	Data relative in pd (subtract neck x,y,z pos) then smoothed using a window size in WekiHelper - size 30.	Input: 12 features Models: 3 continuous one for each compensation (elbow, shoulder & trunk)	Output floats x 3 hard limit between 0.0 and 1.0	NN: 3 hidden layers. Trained on x,y,z features for elbow and shoulder. Neck.y and shoulder.y only for trunk lean.	No sounds used for test - looking at visual in Weki.	8 Model working pretty well. Needed to provide examples of good movement to stabilise to 0.	This seems like the best approach and is the best accuracy. Need to watch trunk lean as neck is NOT relative. Hence z position = same distance from camera front.
10 Camera in front 18th June 2018	Track Hand-to-mouth via 3 poses : try using 3 separate models this time.	Data relative in pd (subtract neck x,y,z pos) then smoothed using a window size in WekiHelper - size 30.	Input: 9 features per mode; Models: 3 continuous one for each compensation (elbow, shoulder & trunk)	Output floats x 3 hard limit between 0.0 and 1.0	NN: 3 hidden layers. Trained on 9 x,y,z features	Same Kick, snare and hat triggers for each pose.	7-8 Models working well providing examples of non triggers are given. This means training takes longer but is more accurate. However too many examples over trains and it gets worse?	Worked best training one model individually at a time. Isolate the record channel in Weki for this. Give lots of examples at 0.0 to stop false triggers.
11	Track a musical scale - arpeggio first then move	Data relative in pd (subtract neck x,y,z	Input: 9 features per mode;	Output float hard limit between 0.0	Linear Regression with no	Triggering piano sounds:	5 the arpeggio is playing c4, e4, g4 and c5.	There is noise on the data coming in that

Camera in front 19th June 2018	onto a full 8 note scale C to C. Use forward reach only	pos) then smoothed using a window size in WekiHelper - size 30.	Model: 1 continuous	and 1.0 and thresholds set in pd to get notes at 0.25, 0.5 and 0.75.	feature selection as default.	c4, e4, g4 and c5.	This sounds ok but the thresholds between notes are not consistent.	can't be smoothed to suit a linear progression such as a scale… this is going to be hard.
12 Camera to right had side 2 oclock 1st July 2019	Trial to get Trunk Leaning better	Data relative in pd (subtract neck x,y pos) smoothed using pole filter in PD			Linear Regression	Song with silence as feedback		If the other arm is left in the accuracy of the tracked arm is far better! This works better and should be the approach from now on. The patient needs to be asked to place both hands on the table at the start position not just the affected arm!!
13 July 2nd 2019	Use only wrist x,y for pose estimation. This seems to be quicker and more reliable?		Elbow Model: elbow and wrist (x,y) Trunk Model: (Neck x,y) Shoulder Model: (shoulder y only - more consistent without x) Pose1: (wrist x,y only) Pose2: (wrist x,y only)	0.0 - 1.0 hard limits	Linear regression	Music and silence as NHS protocol completed		Tried shoulder x,y with the elbow to track elbow. Ended up being most accurate and smooth with elbow and wrist x,y

Appendix 3-2 Goldsmiths University of London Ethics Forms 2017

Music and Movement Tracking to Aid Upper Limb Stroke Rehabilitation
v0.1 EAF2 Ethical Implications – Pedro Douglass-Kirk Oct 2017

EAF2 Ethical Implications

Table of Contents

1 Title of project

Music and Movement Tracking to Aid Upper Limb Stroke Rehabilitation

2 Purpose of project and its academic rationale

Digital approaches to physical rehabilitation are becoming increasingly common, encompassing a range of approaches such as wearable systems, biofeedback systems (Yungher & Craelius, 2012) and robotics (Huang & Krakauer, 2009). The use of sensory feedback has been somewhat explored e.g. (Chen et al., 2006) and several authors note the versatility of the auditory domain in particular to provide feedback on upper limb movements (Scholz et al., 2016).

The purpose of this project is to explore how auditory feedback could aid in stroke rehabilitation, specifically in helping to track upper limb movements. The research will involve consultations with medical staff and feasibility testing sessions with stroke patients to inform the design of a stroke rehabilitation system using auditory feedback.

3 Brief description of methods and measurements

The methods will involve conducting workshops and consultations with medical staff from the Upper Limb Neurorehabilitation Service in the National Hospital for Neurology and

Neurosurgery (NHNN) to obtain their expertise and co-design a new system for stroke rehabilitation.

Additionally, individual feasibility sessions will be conducted with approximately 10 chronic stroke patients attending the Upper Limb Neurorehabilitation Service. These sessions will explore different variations of auditory feedback for upper limb rehabilitation tasks. Patients will provide feedback on factors such as effort, enjoyment, and their perception of the different auditory feedback variations.

Measurements will also be collected using video tracking and machine learning models to quantify movement patterns. Patient questionnaires will gather feedback on subjective factors such as effort and auditory perception. Part of the research is to explore the use of novel technologies and one has been selected to assess in feasibility research called OpenPose. This technology consists of a 2D webcam using the open-source software, *OpenPose* (Cao et al., 2017) and maps that data to provide real-time auditory feedback.

4 Participants: recruitment methods, number, age, gender, exclusion/inclusion criteria.

Participants will be invited to attend workshops to help co-design a new stroke rehabilitation system. These will include medical staff members from the Upper Limb Neurorehabilitation Service, consisting of neurologists, physiotherapists, and occupational therapists. Furthermore, other experts in psychology, and Human Computer Interaction (HCI) will be invited to take part.

Additionally, 10 chronic stroke patients attending the Upper Limb Neurorehabilitation Service will be recruited after some initial workshops with the staff on the Upper Limb Neurorehabilitation Service. Participants will be screened and selected by QSUL staff as suitable candidates for the feasibility research. No personal details will be collected but all will be adults aged 18+ with medical staff in attendance at all times.

Participants will first be invited to take part in the study by the health professionals working at the Upper Limb Neurorehabilitation Service either in the clinic or directly on the stroke unit when they start the programme. They will be given information about the study and asked if they would like to be referred to the research team. They will then be put in contact with one of the members of the research team who will meet face to face with the patient and a member of staff to answer any questions they may have.

4.1 Inclusion criteria

Key inclusion criteria include: (1) acceptance on the Upper Limb Neurorehabilitation Service at the NHNN, (2) diagnosis of stroke resulting in hemiparesis at least 6 months prior to study, (3) ability to give informed consent, (4) the cognitive ability to follow the tasks, (5) the ability to lift the affected hand onto a table whilst seated, unaided by their unaffected limb, (6) the ability to sit unsupported for at least 10 minutes, (7) aged between18-75, (8) right-handed

5 Consent and participant information arrangements, debriefing.

5.1 Patient Information Sheet (for individual sessions)

Participant Information Sheet

Project Title: Music and Movement to Aid Upper Limb Stroke Rehabilitation

Name of Chief Investigator: Pedro Douglass Kirk, PhD candidate Goldsmiths University of London.

Education Project: This research will be conducted in part fulfilment of a PhD.

We would like to invite you to take part in a research study using music and movement with technology. Please take time to carefully read this information sheet and feel free to contact the research team or staff with any questions or concerns you may have. The research team's contact information is at the end of this document.

What is the purpose of the research?
We want to test different versions of a stroke rehabilitation system that uses music and sound feedback. The goal is to help track your movements and give you information about your movements in real time.

Why have I been invited?
Your medical team thinks you would be a good candidate to provide feedback to help improve the system. Your opinions are valuable to help guide the development.

Do I have to take part?
No, participating is completely voluntary. Whether you take part or not will not affect your medical care in any way. You can stop at any time.

What will I need to do?
You will do simple seated reaching tasks while listening to music. You will be asked to select some of your favourite music to move along to. Sensors will track your arm movements. You may hear different sound feedback when you move your arm. We want to get your opinions on effort and enjoyment while moving to music. Medical staff will be present at all times during the session.

How long will each session last?
We expect each testing session to last around 30 minutes. Please let staff know if you need to stop and rest at any point.

What are the benefits of taking part in the study?
You may enjoy moving while listening to your favourite music and you may well have a lot of fun taking part in the study. Your participation will help us better understand how music may be helpful in upper limb rehabilitation.

What are the disadvantages and risks of taking part in the study?
There is risk of fatigue due to the physical exercise you will be undertaking. You can rest at any time during the study if you feel too tired. The upper limb team will be available at all times if you require any support. You may also get uncomfortable sitting for long periods of time so you will be able to move around and have a break at any time if you need to.

Will my information be confidential?
Yes, no personal data will be collected. All data from the sessions will be kept confidential and used to help design a system for stroke rehabilitation. All data will be kept for 5 years and then destroyed.

What will happen to the results of the research study?
Following the study, we plan to publish the results in academic/health-based journals and to present our findings at conferences and meetings so that others can learn from the research. We can also provide you with a copy of any published outputs on request.

Who is organising and funding the research?
This research study is being supervised by Prof Lauren Stewart at Goldsmiths, University of London and by Prof Mick Grierson at Goldsmiths, University of London.

This research study is being conducted by Pedro Douglass-Kirk who is a PhD student at Goldsmiths, University of London as part of an educational qualification.

Also, members of the Upper Limb team are members of the research for this project. Professor Nick Ward, Fran Brander, Kate Kelly will all be involved in helping design a new system that you can support.

Who do I contact?
If you have any questions, please ask at any time. You may contact my PhD supervisor or myself:

Pedro Douglass-Kirk	Lauren Stewart
Music, Mind and Brain PhD student	Professor in Psychology
+44 (0)7749551292	+44 (0)20 7919 7195
mu101pk@gold.ac.uk	l.stewart@gold.ac.uk

Thank you for taking the time to read this information sheet.

5.2 Participant Information Sheet (co-design workshops)

Participant Information Sheet (workshops)

Project Title: Music and Movement to Aid Upper Limb Stroke Rehabilitation

Name of Chief Investigator: Pedro Douglass Kirk, PhD candidate Goldsmiths University of London.

Education Project: This research will be conducted in part fulfilment of a PhD.

We would like to invite you to take part in workshops to co-design a system using music and movement to support stroke rehabilitation of the upper limb.

Please take time to carefully read this information sheet and feel free to contact the research team or staff with any questions or concerns you may have. The research team's contact information is at the end of this document.

Music and Movement Tracking to Aid Upper Limb Stroke Rehabilitation
v0.1 EAF2 Ethical Implications – Pedro Douglass-Kirk Oct 2017

What is the purpose of the research?
We want to test different versions of a stroke rehabilitation system that uses music and sound feedback. The goal is to help track your movements and give you information about your movements in real time

Why have I been invited?
You are invited to attend a series of workshops to provide expertise and feedback to help inform the development of a stroke rehabilitation system using auditory feedback. The workshops will involve discussions around current practices in stroke rehabilitation and how auditory feedback could aid in tracking movements in stroke rehabilitation. There will also be interactive demonstrations of potential system variations for you to test and provide feedback on. Your expertise will be helpful in building a system that has good clinical and usability foundations.

Do I have to take part?
No, participating is completely voluntary.

What will I need to do?
You will be encouraged to try out motion tracking systems running of a webcam and explore the design of the system in the workshops. Your participation will be active with open discussions and testing of system design and auditory feedback. The goal is to gather a range of perspectives to iteratively improve the system design. Any views or suggestions you provide may help shape how auditory feedback is incorporated.

How long will each workshop last?
We expect each workshop to last between 1 and 2 hours.

Who is organising and funding the research?
This research study is being supervised by Prof Lauren Stewart at Goldsmiths, University of London and by Prof Mick Grierson at Goldsmiths, University of London. This research study is being conducted by Pedro Douglass-Kirk who is a PhD student at Goldsmiths, University of London as part of an educational qualification.

Who do I contact?
If you have any questions, please ask at any time. You may contact my PhD supervisor or myself:

Pedro Douglass-Kirk
Music, Mind and Brain PhD student
+44 (0)7749551292
mu101pk@gold.ac.uk

Lauren Stewart
Professor in Psychology
+44 (0)20 7919 7195
l.stewart@gold.ac.uk

Thank you for taking the time to review this information sheet. Your participation is greatly appreciated.

5.3 Participant Consent Form (for individual sessions)

PARTICIPANT CONSENT FORM

To confirm that you are willing to participate in the feasibility research, please fill out this form.

If you have any questions, please feel free to ask.

Please initial

1. I confirm that I have read and understood the information sheet provided.	
2. I have had time to consider my participation, ask any questions and they have been answered sufficiently.	
3. I understand that my participation is completely voluntary, and I am free to withdraw at any time without reason, without my care being affected.	
4. I am willing to take part in the feasibility research by undertaking active forward reaching tasks and providing feedback on my experiences.	
5. I am willing and able to give the time needed to participate in this feasibility research.	
6. I understand that information collected during the feasibility research will only be available to the research team and not shared with Goldsmiths University of London. I give permission for the research team to have access to this information.	
7. I give permission for the medical team and the research team to notify each other (with anonymous identifier) if they notice or if there have been any significant changes in my health.	
8. I understand that the data collected will contain no identifiable personal information. I agree that anonymized data collected about me can be kept, securely, on Goldsmiths University of London Campus and on a pad locked USB drive.	
9. I acknowledge that I will not be paid a sum of money for taking part in this feasibility research.	

Once consent has been obtained the original consent form will be stored securely and one singed copy given to you (the participant) to keep.

Participant Signature____

Date______________________

Researcher Signature____

Date______________________

5.4 Participant Consent Form (co-design workshops)

PARTICIPANT CONSENT FORM

To confirm that you are willing to participate in the workshops, please fill out this form.

If you have any questions, please feel free to ask.

	Please initial
1. I confirm that I have read and understood the information sheet provided.	
2. I have had time to consider my participation, ask any questions and they have been answered sufficiently.	
3. I understand that my participation is completely voluntary, and I am free to withdraw at any time without reason, without my care being affected.	
4. I am willing to take part in the feasibility research workshops by undertaking active forward reaching tasks and providing feedback on my experiences.	
5. I am willing and able to give the time needed to participate in this feasibility research workshops.	
6. I understand that information collected during the feasibility research workshops will only be available to the research team and not shared with Goldsmiths University of London. I give permission for the research team to have access to this information.	
7. I give permission for the research team to transcribe audio recordings of the workshop and use my title in any research outputs.	
8. I understand that the data collected will contain no identifiable personal information. I agree that anonymized data collected about me can be kept, securely, on Goldsmiths University of London Campus and on a pad locked USB drive.	
9. I acknowledge that I will not be paid a sum of money for taking part in this feasibility research workshops.	

Once consent has been obtained the original consent form will be stored securely and one singed copy given to you (the participant) to keep.

Participant Signature____

Date____________________

Researcher Signature____

Date____________________

5.5 Debrief Form

PARTICIPANT DEBRIEF FORM

Title of Project: Music and Movement Tracking to Aid Upper Limb Stroke Rehabilitation

Name of Chief Investigator: Pedro Douglass Kirk, PhD candidate Goldsmiths University of London.

Education Project: This research will be conducted in part fulfilment of a PhD.

Thank you for taking part!

We would like to take this opportunity to say **Thank You** for taking the time to take part in our study using music as part of your physical rehabilitation.

Please be assured, all data collected will be treated in the strictest confidence. You are free to withdraw your data from the research at any time by contacting myself Pedro (mu101pk@gold.ac.uk) or my PhD supervisor Prof. Lauren Stewart (l.stewart@gold.ac.uk).

The completed research will help to gain an understanding of how music can aid stroke rehabilitation. If you were unduly or unexpectedly affected by taking part in the study, please feel free to feed it back to myself. If you feel unable for whatever reason what-so-ever to talk with me then please either contact my supervisor or any of the health experts at the Upper Limb Service.

Who do I contact?
If you have any questions, please ask at any time. You may contact my PhD supervisor or myself:

Pedro Douglass-Kirk	Lauren Stewart
Music, Mind and Brain PhD student	Professor in Psychology
+44 (0)7749551292	+44 (0)20 7919 7195
mu101pk@gold.ac.uk	l.stewart@gold.ac.uk

Thank you for taking the time to read this debrief form.

6 A clear but concise statement of the ethical considerations raised by the project and how you intend to deal with them.

As we will be working with stroke patients, we will need to be careful to account for possible cognitive and fatigue issues. Health experts will be on hand to ensure any concerns patients may have can addressed as soon as they are raised and at least one member of staff will be in attendance at all times. The staff will help screen patients for eligibility and ensure sessions are appropriate to patient's capabilities. Patients will be able to take breaks whenever needed.

7 Estimated start date and duration of project.

The project will start soon after ethical clearance is attained. The feasibility research will then last for 1.5 years up to May 2019. Workshops with experts will be setup initially with individual sessions planned to take place starting in 2018-19 with stroke patients who will complete the feasibility research within the time they spend at the Upper Limb Neurorehabilitation Service at the NHNN.

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Appendix 4-1 Participant Questionnaire Qualitative Table Summary

Table: *Participant Questionnaire: qualitative responses to Q4, Q5 and Q6*

Q4: What type of feedback did you prefer?

P1: Stated that the alarms were not as engaging as the continuous coupled sound feedback and that individual samples were not fun when they tried them on their own stating: *"That would do my head in after a while".* And *"It's just not motivating".*

P3: Preferred the pitch bend-down and found it most useful. *"It went out of tune and back in."*
"Because it is easier to hear."

P6: *"Distortion".*

P8: Preferred the alarm as they stated they were not as tired as the other conditions.

P9: Alarm and silence as feedback were equally useful.

Q5: What type of feedback did you think was most useful and why?

P1: Distortion was better than pitch in his opinion.

P3: *"Pitch because it made it more obvious."*

P6: *"Pure distortion is more aggressive. It is more in your face. The distortion is immediate."*
"Bending a note was more subtle it takes more time to adjust."

Q6: Any other comments?

P1 *"It's like having a physio here saying you are not doing it right isn't it?"*
"Anything that can make it more fun. Repetition is monotonous… the repetition becomes more fun."
"It's a bit like trying to tune your TV in – you're trying to find the right movement".
"When you are training for a marathon you listen to good music and you run".
"Training in the home and learning on your own - this would be good".

P3: *"I think it's a good idea. I think it's a very good idea."*
"If it's something in the future – I think they will do more exercises – I think it will really work".

P4*: "I'm aware of the movement. Keep my elbow in a little bit more."*
Noted how their hearing was an issue and made it harder than it should be to hear.

P6: Asked if they had to move in time with the music.
"When I decided to move outside the envelope it was immediate. That was good."
"I am quite pleased I was able to move those… 10 minutes."
"Is it similar to Xbox?"

P7: *"I don't think we use music enough."*
"Physios know that people do more with music."
"I listen to music in my car and I crank up the stereo, Van Morrison, Fleetwood Mac. All the windows open fab."
"Music will bring back some of our earliest memories."

P8: Mentioned "*stretching my elbow*" multiple times and having to think about the trunk, elbow and shoulder. **P9:** Stated the exercises were useful to "*keep my mind focused."* They could focus on arm and shoulder and be aware of sitting. **P10:** Commented that a continuous signal may be useful for musicians.
Other comments and issues raised in sessions **P2:** Had wrist watch on that caused issues by catching on the table at times. P2 did not seem as engaged perhaps only due to a noted cognitive deficit. **P3:** *"I tried to adjust – I tried to speed up the movement. If I sped up a little bit it seemed to bring the sound back. It sounded like the volume was coming in and coming out*". This was a misunderstanding and better quality speakers were found to help reduce the issue. **P7:** "*Am I allowed to lean at all?". "It is really hard not to lean*."

Note: P = Participant; direct quotes are in italics and Session notes are in standard text.

Appendix 4-2 Post Session Reflexive Notes

Table *Post Session Questions & reflexive session notes*

Question Number	Question and session number
Q1	Does the system work effectively? **S1**: Not good enough. Both participants had very weak arms and needed support from their unaffected hand **S2:** There are issues with rep tracking, block tacking and other. The system needs to be rebuilt with more automated functionality. **S3:** No reps did not work effectively for P2. Pose 1 and 2 were not recognized well enough maybe due to the lighting and a grey hoodie that seemed to cause tracking issues for the camera. **S4:** There was an issue in that P4 started to pull back behind his start position (due to exercises he normally does). This meant that the system gave the wrong feedback at these points. Retraining solved this issue. The rep counter is working well now and appears accurate. Consider using a loud speaker as the distortion is not as effective as it may be particularly for those who have any hearing issues using the laptop speakers only. **S6:** The camera may have been a different position relative to the participant. **S7:** When a participant pauses, they tend to slouch a little and relax meaning that the compensation feedback is activated quite a lot. System should only collect data during active session not in rest blocks. Consider using sensor fusion with an accelerometer on the wrist to have a little more data to work with.
Q2	Do participants notice the auditory feedback? **S1:** They both noticed the error. However, active movement for both was very poor and triggered very extreme jumps in the sound. Speeding up the sound made P2 laugh

	S2: Yes, the majority of time – however, effort needs to be considered in the tasks and how that influences their ability. **S3:** P1 did at times. P2 no sonification was triggered as they were too good at the task. **S4:** Yes - P4 heard the error well in all 4 conditions. **S6:** Yes. P6 has good hearing ability. **S7:** Yes - P8 did but they moved fast during training with quite restricted examples during the “optimum movement” phase. This meant the training examples likely included too much compensation. This meant P8 did not get as much feedback as they may have done.
Q3	Can participants use this information effectively? **S1:** Not well. P1 was very positive but neither P1 or P2 had enough movement to do the tasks very well. Also, the models were not as well trained as they needed to be. **S2:** A little – at times extreme effort stopped the ability of P1 to change his movements based on the sound as he could not pay attention to the auditory changes. **S3:** P1 was able to at times but due to hearing issues confused how the feedback related to their movement. Shows need for an auditory perception test. **S4:** Yes P4 was able to more efficiently using the feedback at times. **S6:** They seemed to make use of it. But the distortion was very subtle at times. This made it ambiguous when the participant went above the threshold. **S7:** P8 was aware of needing to move with no ambiguity to the sounds it was clear.
Q4	Do participants express a preference for a certain type of feedback? **S1:** No real preference – although there was no explicit question about this feedback. P1 only tried the pitch bend feedback. Furthermore, due to the issues with smoothness of feedback and not explaining (intentionally) what was happening. **S2:** Yes - P1 stated preferring distortion over, pitch and alarms. P2 did not mention it and was not asked. **S3:** P1 found the pitch change the most useful as they could perceive this the easiest. **S4:** Yes - low pitch was his preference. Consider adding in the pitch going up as another feedback type. Would this be more in keeping with “sound affordance”? As the elbow rises up when in error space will a heightening in pitch be more preferred and more useful? **S7:** Due to tiredness P8 stated preferring the first block they did. This shows the importance of counterbalancing.

Q5	What are the optimum number of movements and rest periods? **S1:** P1 needed rests after 1 min. P2 could do active assisted for a long time but got tired doing active blocks. **S2:** Active was hard. Focused on 10 repetitions at a time with P2 with rest blocks. **S3:** P3 managed around 30-40 reps per block using paper to help slide. P4 found the task too easy – next week try a session with reach and lifting the arm up to reach and grab task to make it harder or reach and press a mouse / telephone. **S4**: P4 was able to go for the majority of the 2 min blocks. He had short rest breaks occasionally. **S6**: P7 had cramping of hand and feet so struggled to do many repetitions and required multiple rests. **P6:** was able to achieve 90 second blocks with rests rated as low effort **S7:** P8 needed rests regularly and maybe as the PT suggested 8-12 reps at a time per block may actually be best. Consider programming the system to have a definite rest period between active reps to pause the whole system

Note: S = Session; P = Participant

Table: Technical Session Notes Example

Item	**Session 1 Overview Wednesday 1st Aug 2018**
	The sessions today were helpful in highlighting weaknesses in the system and possible issues with the feedback. For simplicity exercises use self-selected song(s) only with various types of continuous negative feedback. However, based on the sessions summarized testing alarms would be useful to assess. It may be that some patients could find alarms layered over the music as easier to understand and correct their movements to. This is an open question.
1	**Task** Reaching forward to a computer mouse with the aim of pressing it. The physiotherapist stated a light switch would also be a good functional task to use –

	although a suitable prop for this needs to be acquired. The computer mouse was available and added the element of function staff would like to have embedded in the training paradigm
2	**Conditions** 5 possible auditory blocks aiming for 2 minutes completing as many reps as feel comfortable at patients own pace: i) music only, ii) pitch slide down, iii) distortion, iv) speed up tempo, v) slow down tempo.
3	**Kinematic Data Collection** A system to collect the kinematic data and anonymized ID etc. has been tested and is working to generate a text file with time and date every 20ms.
4	**Training the system** The key training consisted of taking the coordinates (x,y) of the elbow position for: 1. "optimum movement pattern" (2 full active assisted (AA) forward reach examples were provided to train the system). Despite having the stronger arm supporting the system could track the affected limb. Note: AA was used as both pts had low function. Both pts also tried to provide a fully active "optimum" but this was quite erratic due to high effort that the movement pattern did not create a consistent difference to the following overcompensation pattern. Therefore, the models generated in this case were possibly not good enough to provide meaningful feedback (this requires further testing) 2. "overcompensation pattern" (i.e. abduction). This was achieved by permitting them to use a fully active movement pattern – both pts found this very effortful, and their elbow came out a long way and

	trunk leaning was immediately evident requiring some physical support at times. As the start pose (hand resting on the edge of the table with ulner styloid at table edge) and end pose (hand pressing on a mouse) were not triggering specific sounds and a method for counting the number of repetitions was not set up in time no training of specific poses was attempted for these sessions. Rather, the key focus was to ascertain the current effectiveness of negative feedback by manipulating self-selected songs. Questions relating to effort and preference were also asked after each block of movements.
5	System Setup The camera was setup directly in front (12 o'clock) from the patient. This meant the trunk leaning was not very accurate. In future sessions move camera to a 2 o'clock or 10 o'clock for right or left affected respectively. The current system took the elbow data and mapped this onto the various sound filters as listed above. There were three issues that need to be looked at in detail to improve on the current system: 1. Some filters were scaling in the opposite direction with different thresholds required to create transitions. More time is required to scale and encode the order. As a solution was not found in advance of the session two separate elbow models were trained. One from 0 – 1 and the other from 1 – 0. This is computationally expensive, and a simple formula has since been worked out to solve this reversing issue (input * -1 + 1 = output). 2. Some filters when activated creating an obvious timbral difference to the clean track. An attempt to reduce this difference by setting a threshold where the sound output heard would change based on

		negative activation. If the slider hit a threshold > 0.2/0.8 then negative feedback would be heard else if < 0.2/0.8 then the full track was heard, and the filters were cut off from being heard entirely. This approach ensured high quality sound when the movement was “optimal”, however, it did not generate an entirely smooth transition from “optimal” to negative feedback (i.e. the jump of 0.2 on the slider meant there was an audible skip from high quality sound to degraded sound that made for large jumps in quality of sound that need to be addressed. Pt 2 certainly complained of “extreme jumps” that this issue may have significantly contributed to. This is a core issue as the aim is for high quality sound output until a certain threshold is reached and this is a technical challenge for the next sessions. 3. Smoothing data: currently no filter was activated, and a linear regression was used as this seemed to be more consistent than the 3 layer neural network during some testing prior to the sessions. A pole filter has been trialled and needs more testing to implement fully.

Appendix 5-1 Participant Information Sheet Lab Experiments 1A and 2A

Stroke Rehabilitation Research

We would like to invite you to take part in a research study using music and movement.

Participant Information Sheet

Scientific Title of Research: Sonic Sleeve: Reducing Compensatory Movements in Stroke Rehabilitation with the Aid of Auditory Feedback

Name of Chief Investigator: Pedro Douglass Kirk, PhD candidate Goldsmiths University of London.

Education Project: This research will be conducted in part fulfilment of a PhD.

IRAS Project ID Number: 251741

ISRTCN trial registration REF: ISRCTN12969079

Ethical approval has been given from London Dulwich REC

Version 0.5 July 2019

Please take time to carefully read this information sheet and feel free to contact the research team with any questions or concerns you may have. The research team's contact information is at the end of this document.

What is the purpose of the study?
We aim to understand how music can help stroke survivors with their upper limb rehabilitation. The key goal of the research is to see if providing auditory feedback on compensation (such as trunk leaning) can help to promote better movement patterns. Research suggests that if stroke patients can reduce undesirable compensatory movements then they may achieve more consistent and efficient movement patterns.

Why have you been chosen?
You are being invited to take part in this research because your medical team at the Upper Limb Neurorehabilitation Service at the National Hospital For Neurology and Neurosurgery think you would be a good candidate for this study.

Do I have to take part?
Taking part in the study is completely voluntary. You may decide to stop being a part of the research study at any time without explanation.

How long will the study be?
You will need to undertake an assessment with the Upper Limb Team to make sure you can take part in the study with some short follow-up tests. This process will take around 20 minutes to complete. Your involvement in the study would require you to undertake four separate sessions in the upper limb clinic. The four sessions will take around 2 hours 45 minutes over the first few weeks of your three week stay on the upper limb clinic.

1. Session 1: to practice and will help familiarize you with the study taken in the first week of your Upper Limb Course
2. Session 2: will be 45 minutes the day after you finish session 1
3. Session 3: will last 1 hour and be one week after session 2
4. Session 4: will last 30 minutes and take place 24 hours after you complete session 3.

What do I have to do?
You will come to a room on the stroke unit for all 4 sessions of the study. Before each session you will fill out the St. Mary's Hospital Sleep Questionnaire to let us know about your sleep quality. And then after each session you will answer a simple question: How tiring did you find taking part in this session? [Not at all, a little, rather, very, extremely]. The initial assessment with staff as mentioned above (session 1) will be completed first followed by some simple tests to make sure you can take part in the study. You will also be asked to choose 10 of your favorite pieces of music at the practice session. We will have lots of music and songs to listen to from Spotify (an online streaming service) to help you choose ones that you like. The music you choose will be used in sessions 2, 3 and 4 only.

You will be listening to music while you move. There will be a 2D webcam that sends video to a system we have built for the study to provide feedback on compensatory movements such as trunk leaning (leaning forward). You will need to do some basic movements to help train the system to track your movements. The training requires you to move your hand from a start position with your wrist on the edge of a table forward to a button marked with an X five times (see image below). You will need to sit up nice and straight with your shoulders relaxed and elbow in towards your body. After this you will need to hold three positions for 5 seconds at a time set by a health expert: 1) hold your affected elbow out at an angle, 2) lean forward by a certain amount and 3) lift up your affected shoulder by a certain amount. After this, you will need to hold your hand on the edge of the table at the start position for 5 seconds, then move your hand forward to the button and hold it there for 5 seconds. This will complete the training sequence.

As part of the first practice session, you will then be required to make some active forward-reaching movements while you sit at a table. See the image below - it shows how a participant will sit and move forward to touch a button. You need to move forward and back five times at a comfortable speed for us to set the speed of your movements. We will then select some music that matches your natural pace.

You will then move along to the music as a practice to get familiar with the setup for 50 repetitions. There will be a 10 second rest after every 10 movements you make. Then there will be at least two minutes rest after every 50 movements you undertake. You will be able to rest at any time during the session if you feel too tired. Sometimes when you move in the sessions you may receive feedback if you compensate by 1) leaning forward, 2) if your elbow comes out to the side too much or 3) if your shoulder lifts up too much. If you compensate the music may stop and you will need to try and get the music to play again by relaxing back into a good posture with your back straight and elbow in. After this first practice session is over there will be two phases to the main study. After all four sessions, you will be asked to fill out a rating of how tired you feel.

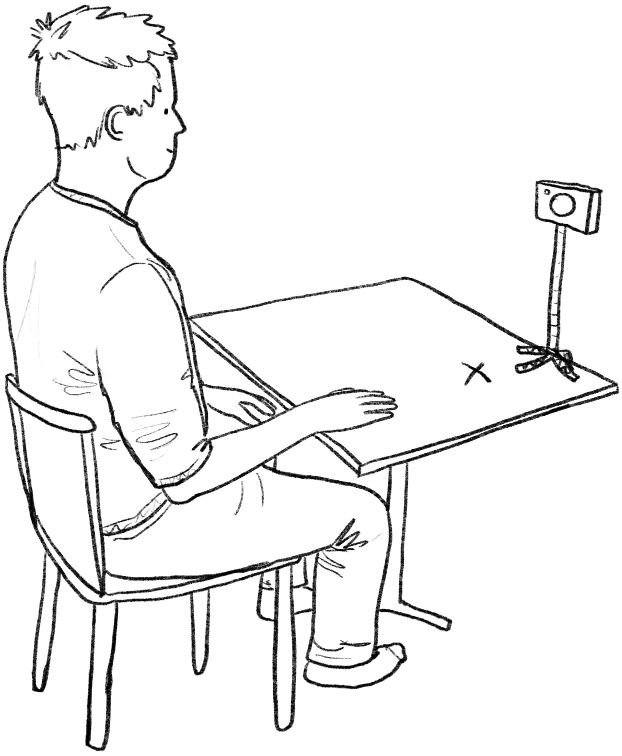


Figure 5: The image shows a patient sitting ready to move forward to a button marked with an X.

Phase 1:
You will come in for session two, and we will check that the system is working as it did in the practice session by doing the same movement reaching to the button 5 times. Then you will undertake two blocks of 50 repetitions with a 2-minute break between the blocks and a 10 second rest every 10 repetitions. You will be moving to the music you selected in the practice session. In one of the blocks you will hear the music cut out if you use compensation (such as trunk leaning, elbow coming out or shoulder lifting up) providing feedback to help you move back to a more optimal movement. In the other block you won't get the feedback. The order of the blocks is like flipping a coin. So you may start with the feedback or without it. In both blocks you need to try and move without compensating.

Phase 2:
A week after phase 1 is finished you will come in for session 3. You will undertake 300 repetitions moving to your favourite self chosen music split into 6 blocks of 50 repetitions. You will be randomised into either an active group where you will receive feedback in some of the movement blocks or a control group where you will not receive feedback in any of the blocks.

The randomisation process will use a random number generator common in psychology research (https://www.randomizer.org/#randomize). Both groups will undertake the 300 repetitions with 10 second rests every 10 repetitions and a 2-minute rest every 50 repetitions. If you are in the active group you will undertake the first and final bock of 50 repetitions without any feedback. During the middle 4 blocks of 200 repetitions you will receive feedback in the active group.

For the final session (number 4) which will take place 24 hours later, you will just be undertaking 50 repetitions of the movements without any feedback. This will be the end of the study.

What are the benefits of taking part in the study?
You may enjoy moving while listening to your favorite music. Your participation will help us better understand how music may be helpful in upper limb rehabilitation.

What are the disadvantages and risks of taking part in the study?
There is risk of fatigue due to the physical exercise you will be undertaking. You can rest at any time during the study if you feel too tired. The upper limb team will be available at all times if you require any support. You may also get uncomfortable sitting for long periods of time so you will be able to move around and have a break at any time if you need to.

Will my participation in this study be kept confidential?
All information collected about you during the course of the research will be kept strictly confidential and will be stored on secure University servers.

Goldsmiths University of London is the sponsor for this study based in the United Kingdom. We will be using information from you and your medical records in order to undertake this study and will act as the data controller for this study. This means that we are responsible for looking after your information and using it properly. Goldsmiths University of London will keep identifiable information about you for 5 years after the study has finished.

Your rights to access, change or move your information are limited, as we need to manage your information in specific ways in order for the research to be reliable and accurate. If you withdraw from the study, we will keep the information about you that we have already obtained. To safeguard your rights, we will use the minimum personally-identifiable information possible.

You can find out more about how we use your information by contacting the Chief Investigator Pedro Douglass-Kirk via email mu101pk@gold.ac.uk.

The research team on the NHS upper limb programme will use your name, NHS number and contact details to contact you about the research study, and make sure that relevant information about the study is recorded for your care, and to oversee the quality of the study. Individuals from Goldsmiths University of London and regulatory organisations may look at your medical and research records to check the accuracy of the research study. The NHS upper limb service will pass these details to Goldsmiths University of London along with the information collected from you and your medical records. The only people in Goldsmiths University of London who will have access to information that identifies you will be people who need to contact you to follow-up with you or audit the data collection process. The people who analyse the information will not be able to identify you and will not be able to find out your name, NHS number or contact details. The NHS upper limb service will keep identifiable information about you from this study for 5 years after the study has finished.

Goldsmiths University of London will collect information about you for this research study from the NHS upper limb service. This information will include your name, NHS number, contact details and health information. Further demographic information will also be collected including age, SES (annual income), ethnicity, marital status (married, partner or single), occupation, education, medication, contact information (phone number and email), details of your stroke, and lifestyle information, which is regarded as a special category of information. We will use this information to help with our interpretation of results. If information about your medical history is used in medical or scientific publications no identifying information will be linked to the information. All data will be kept for 5 years and then destroyed. Once consent has been obtained the original consent form will be stored in the Investigator Site File with one copy stored in your medical notes and one copy given to you for reference.

Are there any differences compared to standard care?
Standard care on the upper limb service is an intensive programme where you will need to do physical activities for 6, five days a week for three full weeks totalling 90 hours. There will be a whole range of physical exercises and goal setting you will undertake on the upper limb service that you will have discussed during your clinic session with medical staff. There will

be no travel costs associated with the study as you will be on the stroke unit as part of your standard care.

Taking part in the study will differ to the standard care you would get on the upper limb service in a number of ways. Firstly, you will be required to have the short assessment with the medical staff and some basic screening tests with a researcher to make sure you can take part in the study.

Secondly, you will be required to fill out two short questionnaires at each session that are not part of standard care. Before each session you will fill out the St. Mary's Hospital Sleep Questionnaire to let us know about your sleep quality. And then after each session you will answer a simple question: How tiring did you find taking part in this session? [Not at all, a little, rather, very, extremely].

Thirdly, you will be undertaking the forward-reaching exercises in the research that may be a little different from some of the other exercises on the upper limb programme where you work with physiotherapists and occupational therapists. The staff will ensure that the exercises you do in the study are relevant for your upper limb programme. The study sessions will become part of your timetable. There are 4 sessions over the three weeks you are on the upper limb course as stated above that will take approximately 2 hours 45 minutes to complete.

What will happen to the results of the research study?
Following the study, we plan to publish the results in academic/health-based journals and to present our findings at conferences and meetings so that others can learn from the research. We can also provide you with a copy of any published outputs on request.

As a university in collaboration with the NHS upper limb service, we use personally-identifiable information to conduct research to improve health, care and services. As a publicly-funded organisation, we have to ensure that it is in the public interest when we use personally-identifiable information from people who have agreed to take part in research. This means that when you agree to take part in a research study, we will use your data in the ways needed to conduct and analyse the research study. Your rights to access, change or move your information are limited, as we need to manage your information in specific ways in order for the research to be reliable and accurate. If you withdraw from the study, we will keep the information about you that we have already obtained. To safeguard your rights, we will use the minimum personally-identifiable information possible.

Health and care research should serve the public interest, which means that we have to demonstrate that our research serves the interests of society as a whole. We do this by following the UK Policy Framework for Health and Social Care Research.

Who is organising and funding the research?
This research study is being supervised by Professor Lauren Stewart at Goldsmiths, University of London and by Professor Mick Grierson at The Creative Computing Institute. This research study is being conducted by Pedro Douglass-Kirk who is a PhD student at Goldsmiths, University of London as part of an educational qualification. Also members of the Upper Limb team are members of the research for this project. Professor Nick Ward, Fran Brander, Kate Kelly, Will Chegwidden and Dhiren Shivji have all helped with setting up the study and will be helping to ensure all patients are undertaking appropriate movements.

Who do I contact?
If you have any questions please ask at any time. You may contact my supervisor or myself:

Pedro Douglass-Kirk	**Lauren Stewart**
Music, Mind and Brain PhD student	Professor in Psychology
07749551292	020 7919 7195
mu101pk@gold.ac.uk	l.stewart@gold.ac.uk

Who do I contact if I have a complaint?
If you wish to raise a complaint on how we have handled your personal data, you can contact our Data Protection Officer who will investigate the matter. If you are not satisfied with our response or believe we are processing your personal data in a way that is not lawful you can complain to the Information Commissioner's Office (ICO) via their website (https://ico.org.uk) or call them on 0303 123 1113. Our Data Protection Officer is Matthew Ramsey and you can contact him via email dp@gold.ac.uk or call 02079 197 171.

If you are not satisfied with your hospital experience please speak to the person in charge of the ward or clinic. In this case you can contact Professor Nick Ward:
Tel: 020 3448 3924
Email: n.ward@ucl.ac.uk

We are keen to ensure the highest standards of patient care and will try to resolve any problems quickly. You can also speak to our Patient Advice and Liaison Service (PALS) who will help with your problem quickly and informally. Contact PALS on 020 3447 3042.
If you are still not satisfied you can make a formal complaint. This will not affect your hospital treatment in any way.

To make a formal complaint to UCLH
You can do this within 12 months of the events concerned, or within 12 months of becoming aware of the problem. Your complaint will be recorded as part of our formal complaints policy. Please write with full details to the Chief Executive (details above) or to the Complaints Manager at:
Quality and Safety Department, UCLH
2nd Floor West
250 Euston Road
London
NW1 2PG
Telephone: 020 3447 7413
Email: uclh.complaints@nhs.net

Thank you for taking the time to read this information sheet.

Appendix 5-2 Participant Consent Form All Experiments

Scientific Title of Research: Sonic Sleeve: Reducing Compensatory Movements in Stroke Rehabilitation with the Aid of Auditory Feedback

To confirm that you are willing to participate in the research study, please fill out this form.

If you have any questions please feel free to ask.

	Please initial
1. I confirm that I have read and understood the information sheet provided.	
2. I have had time to consider my participation, ask any questions and they have been answered sufficiently.	
3. I understand that my participation is completely voluntary and I am free to withdraw at any time without reason, without my care being affected.	
4. I am willing to take part in the study by undertaking active forward-reaching tasks while being filmed with a webcam to track my movements.	
5. I understand that information collected during the study (medical information, answers to questionnaires) may be required for the research. I give permission for the research team to have access to this information.	
6. I give permission for the medical team and the research team to notify each other (with anonymous identifier) if they notice or if there have been any significant changes in my health.	
7. I agree to allow the research team to have my phone number and email and I understand that all my personal information will be kept confidential.	
8. I agree that personal information collected about me can be kept, securely, on Goldsmiths University of London servers that only the research team has access to.	
9. I acknowledge that I will not be paid a sum of money for taking part in this study.	

Once consent has been obtained the original consent form will be stored in the Investigator Site File with one copy stored in your medical notes and one copy given to you (the participant) for reference.

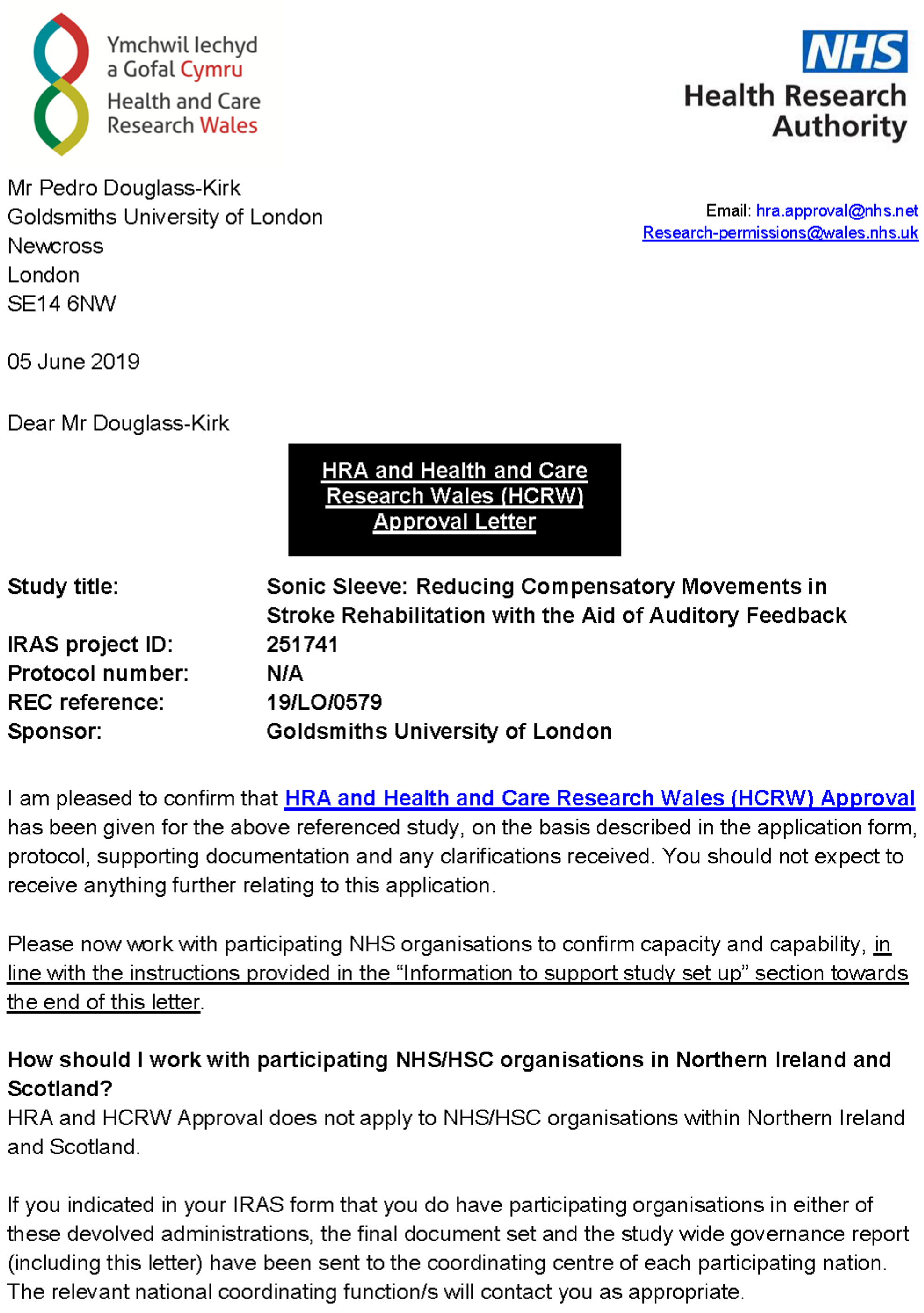
Participant
Signature____

Date______________________

Researcher
Signature____

Date_____________________

Appendix 5-3 NHS Ethical Approval REC 19/LO/0579



Ymchwil Iechyd
a Gofal Cymru
Health and Care
Research Wales

NHS
Health Research
Authority

Email: hra.approval@nhs.net
Research-permissions@wales.nhs.uk

Mr Pedro Douglass-Kirk
Goldsmiths University of London
Newcross
London
SE14 6NW

05 June 2019

Dear Mr Douglass-Kirk

HRA and Health and Care Research Wales (HCRW) Approval Letter

Study title:	**Sonic Sleeve: Reducing Compensatory Movements in Stroke Rehabilitation with the Aid of Auditory Feedback**
IRAS project ID:	**251741**
Protocol number:	**N/A**
REC reference:	**19/LO/0579**
Sponsor:	**Goldsmiths University of London**

I am pleased to confirm that HRA and Health and Care Research Wales (HCRW) Approval has been given for the above referenced study, on the basis described in the application form, protocol, supporting documentation and any clarifications received. You should not expect to receive anything further relating to this application.

Please now work with participating NHS organisations to confirm capacity and capability, in line with the instructions provided in the "Information to support study set up" section towards the end of this letter.

How should I work with participating NHS/HSC organisations in Northern Ireland and Scotland?

HRA and HCRW Approval does not apply to NHS/HSC organisations within Northern Ireland and Scotland.

If you indicated in your IRAS form that you do have participating organisations in either of these devolved administrations, the final document set and the study wide governance report (including this letter) have been sent to the coordinating centre of each participating nation. The relevant national coordinating function/s will contact you as appropriate.

Please see IRAS Help for information on working with NHS/HSC organisations in Northern Ireland and Scotland.

How should I work with participating non-NHS organisations?
HRA and HCRW Approval does not apply to non-NHS organisations. You should work with your non-NHS organisations to obtain local agreement in accordance with their procedures.

What are my notification responsibilities during the study?

The document "*After Ethical Review – guidance for sponsors and investigators*", issued with your REC favourable opinion, gives detailed guidance on reporting expectations for studies, including:

- Registration of research
- Notifying amendments
- Notifying the end of the study

The HRA website also provides guidance on these topics, and is updated in the light of changes in reporting expectations or procedures.

Who should I contact for further information?
Please do not hesitate to contact me for assistance with this application. My contact details are below.

Your IRAS project ID is **251741**. Please quote this on all correspondence.

Yours sincerely,

Emma Stoica
Approvals Manager

Email: hra.approval@nhs.net

Copy to: *Dr Caroline Rix*
Professor Lauren Stewart

List of Documents

The final document set assessed and approved by HRA and HCRW Approval is listed below.

Document	*Version*	*Date*
Copies of advertisement materials for research participants [Recruitment Poster - Track Changes]	0.3	02 May 2019
Copies of advertisement materials for research participants [Recruitment Poster - Clean Copy]	0.3	02 May 2019
Covering letter on headed paper [Covering Letter from CI]	0.1	26 March 2019
Evidence of Sponsor insurance or indemnity (non NHS Sponsors only) [Professional Indemnity Certificate Insurance 2019]	0.1	02 May 2019
HRA Schedule of Events	HRA v1	23 May 2019
HRA Statement of Activities	HRA v1	23 May 2019
IRAS Application Form [IRAS_Form_13032019]		13 March 2019
Letter from funder [Letter From Goldsmiths University of London]	0.1	26 March 2019
Non-validated questionnaire [Sonic Sleeve Tiredness Rating Scale]	0.1	26 March 2019
Other [Part C: Site UCLH]	0.1	13 March 2019
Other [A13 IRAS UPDATE]	0.1	02 May 2019
Other [GCP Certificate fro CI]	0.1	17 July 2018
Other [Response Letter to REC]	0.1	02 May 2019
Participant consent form [TC]	0.3	24 May 2019
Participant consent form [clean copy]	0.3	24 May 2019
Participant information sheet (PIS) [clean copy]	0.4	05 June 2019
Participant information sheet (PIS) [TC]	0.4	05 June 2019
Research protocol or project proposal [Sonic Sleeve Protocol - tracked]	0.2	02 May 2019
Research protocol or project proposal [Sonic Sleeve Protocol]	0.2	02 May 2019
Summary CV for Chief Investigator (CI) [CI CV]		13 March 2019
Summary CV for supervisor (student research) [Academic Supervisor CV]	0.1	26 March 2019
Summary, synopsis or diagram (flowchart) of protocol in non technical language [Flow Chart - Track Changes]	0.2	02 May 2019
Summary, synopsis or diagram (flowchart) of protocol in non technical language [Flow Chart - Clean Copy]	0.2	02 May 2019
Validated questionnaire [The St Mary's Hospital (SMH) Sleep Questionnaire]	0.1	26 March 2019

IRAS project ID	251741

Information to support study set up

The below provides all parties with information to support the arranging and confirming of capacity and capability with participating NHS organisations in England and Wales. This is intended to be an accurate reflection of the study at the time of issue of this letter.

Types of participating NHS organisation	Expectations related to confirmation of capacity and capability	Agreement to be used	Funding arrangements	Oversight expectations	HR Good Practice Resource Pack expectations
One NHS organisation is participating in the study as All Site Activity type.	Research activities should not commence at participating NHS organisations in England or Wales prior to their formal confirmation of capacity and capability to deliver the study.	A statement of activities has been submitted and the sponsor is not requesting and does not expect any other site agreement to be used.	The sponsor is not providing any funding to the participating site.	A Principal Investigator should be in place at the host NHS organization.	Where no prior arrangements are in place with the host NHS organisation, external researchers undertaking research activities at the NHS site would be expected to obtain honorary research contracts based on Research Passports (if University employed) or Letters of Access based on NHS to NHS confirmation of pre-engagement checks letter (if NHS employed). These should confirm enhanced DBS checks and occupational health clearance.

Other information to aid study set-up and delivery

This details any other information that may be helpful to sponsors and participating NHS organisations in England and Wales in study set-up.

- Part C of the IRAS form has not been completed but the missing information is provided in a separate document (IRAS Application PART C).
- The applicant has indicated that they do not intend to apply for inclusion on the NIHR CRN Portfolio.

Appendix 5-4 Goldsmiths University of London Ethics Forms 2019

Sonic Sleeve v 0.1 EAF2 Ethical Implications – Pedro Douglass-Kirk Feb 2019

EAF2 ETHICAL IMPLICATIONS

Contents

1 Title of project.

Sonic Sleeve: Reducing Compensatory Movements in Stroke Rehabilitation with the Aid of Auditory Feedback

2 Purpose of project and its academic rationale.

Stroke is a leading cause of adult disability (Benjamin et al., 2018) and rehabilitation of the upper limb is typically inadequate. Digital approaches to physical rehabilitation are becoming increasingly common, encompassing a range of approaches such as wearable systems (Wang et al., 2017), biofeedback systems (Yungher & Craelius, 2012) and robotics (Huang & Krakauer, 2009). The use of sensory feedback has been somewhat explored e.g. (Chen et al., 2006) and several authors note the versatility of the auditory domain in particular to provide feedback on upper limb movements (Scholz et al., 2016; Sigrist et al., 2015).

However, despite these efforts to investigate the potential for digital approaches to provide real-time feedback in rehabilitation, this line of research is limited when applied to tackling the undesirable compensatory movements that often accompany goal-directed movements in stroke patients. Feedback on compensatory trunk leaning has been investigated with visual and force feedback (Lancelot et al., 2014) and augmented feedback (Valdes Benavides, 2017), but, there is a lack of research on the use of real-time auditory feedback on these undesirable compensatory movements.

In a typical therapy session, a physiotherapist will encourage optimal movements with verbal and physical manoeuvring of the patient. Could the use of technology that can automatically signal when compensation is occurring be a useful rehabilitation aid? The current project is a first step towards investigating whether a digital system can provide relevant real-time feedback (specifically in the auditory domain) to help reduce compensatory movements.

In prior research we established that self-selected favourite music provides a motivating context for physical therapy, with patients engaging in hundreds of repetitions of their target movements (Kirk et al., 2016). This provides an excellent context in which to additionally incorporate real-time information in the auditory domain about the extent to which their movement is within optimal movement settings, as determined by a health expert who will be involved in parameter setting for each participants before the experiment begins.

The primary question is: **Can stroke patients perceive and make use of auditory feedback (muting within self-selected music) to reduce compensatory movements in a seated active forward reaching task?** This question will be investigated in two phases. Phase 1 will establish if patients can make use of the feedback and reduce compensation (trunk leaning, shoulder abduction or shoulder elevation). The second phase will investigate whether training with this feedback will promote learning such that reduced compensation will also be seen in the absence of auditory feedback.

We have two key hypotheses relating to our research question:

- Stroke patients undertaking active forward reaching movements while listening to self-selected favourite music will reduce compensatory movements when they receive feedback compared to no feedback.
- Stroke patients who engage in a training session with this feedback for 200 repetitions will learn to reduce compensation even when this feedback is no longer present. This will be investigated at two time points: immediately after the training phase and 24 hours later.

3 Brief description of methods and measurements

3.1 Target Movement

The target movement for the study is a seated active forward reaching task (see Figure 1). For a single repetition patients will begin with the mid-point of the ulnar styloid positioned exactly at the edge of the table with elbow in line with the centre of their torso on the hip. From here, the participants will move their affected limb forward to a target marked on the table (set at an appropriate reaching distance by the health experts) before returning to the start position.

Feasibility testing in the ULS has revealed that patients take between three and five seconds to complete a single repetition at their natural preferred baseline tempo. Every 10 repetitions there will be a short rest of 10 seconds. After every 50 repetitions they will be given a longer rest of at least 2 minutes. Patients will be made aware they can request longer rest breaks at any time they want to. Patients will move to self-selected music that has been matched to their baseline movement tempo.

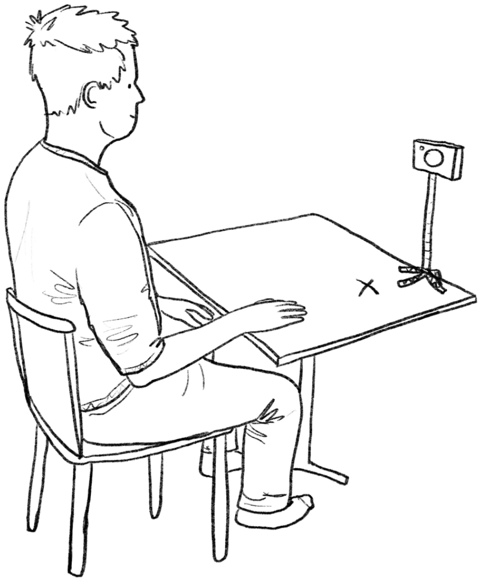


Figure 1: The patient will be seated upright with their wrist on the edge of the table. They will move their hand forwards to reach target X before returning to the original start position. A 2D webcam will take video footage of their movement and send kinematic data into a machine learning system as described in section 4.3 below.

3.2 Design

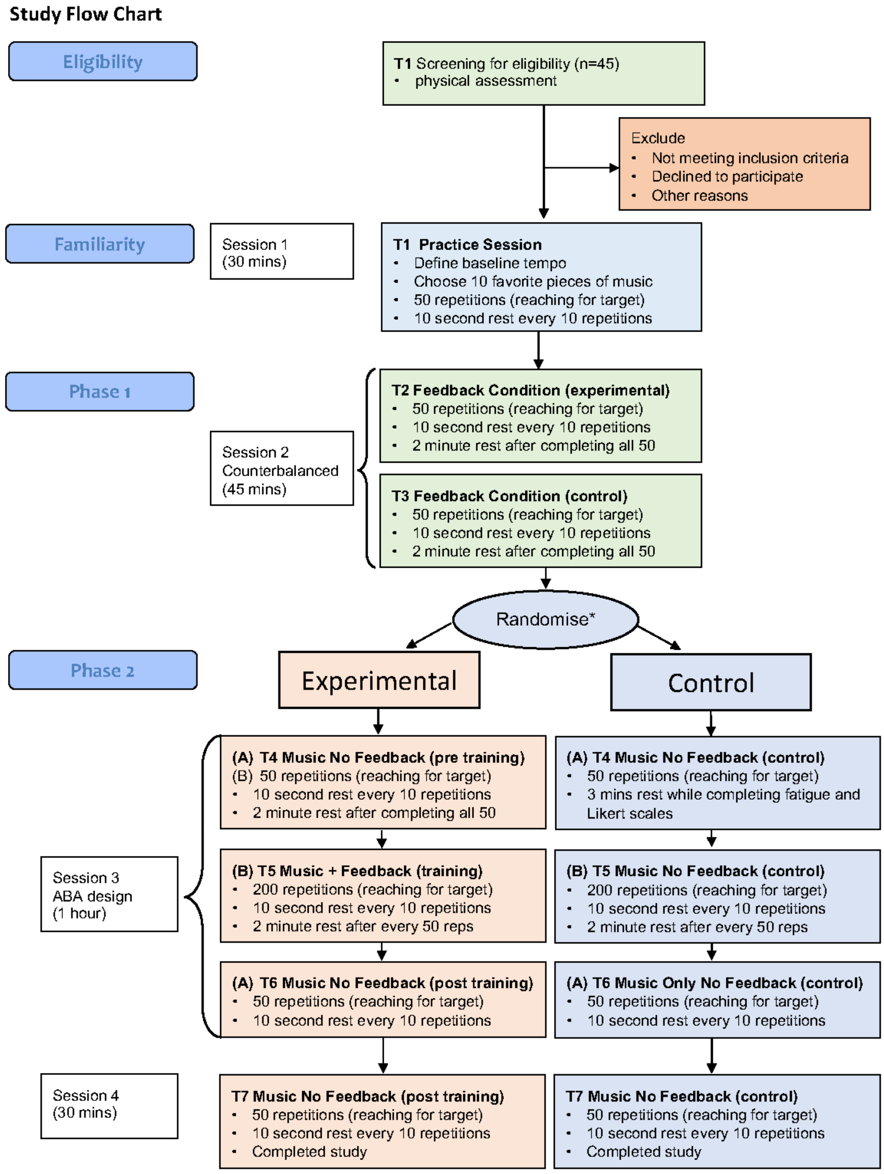
Phase 1

This will use a within-subject design with two conditions (experimental vs. control) presented in a counterbalanced order. In the experimental condition patients will undertake 50 repetitions of an active forward reaching movement while listening to self-selected favourite music that incorporates real-time auditory feedback using the Sonic Sleeve system described in section 4.3. If patients use compensatory movements (i.e. trunk leaning or shoulder abduction) the music will be muted until they correct their posture and continue with the ongoing movement. In the control condition patients will undertake 50 repetitions, again moving to the same self-selected music but without any feedback to signal when compensatory movements are occurring.

Phase 2

Patients who show a significant effect of feedback on the reduction of compensatory movements will be randomized into the experimental or control group of Phase 2. In Phase 2, participants will train on the forward reach movement for a total of 200 repetitions, either with feedback (experimental group) or without (control group). By comparing the amount of compensatory movement occurring in a single session of 50 repetitions after training, compared with a session of 50 repetitions before training, we will investigate whether training with feedback, compared with training without feedback, reduces compensation even when the feedback signal is no longer present. Although learning effects are normally investigated following longer training sessions than this, a study by Cirstea, Ptito, & Levin, 2003 was able to demonstrate short term learning effects on a pointing task following visual guidance feedback.

3.3 Study Flow Chart



Note: * If patients have been able to use feedback to modify their compensation (i.e. there is a significant reduction in time spent compensating with feedback vs no feedback conditions) they move onto Phase 2 randomised into either experimental or control groups.

3.4 Sonic Sleeve Measurements

Sonic Sleeve is a system developed for the current study that takes kinematic movement data from a 2D webcam using the open-source software, *OpenPose* (Cao, Simon, Wei,

& Sheikh, 2017) and maps that data to provide real-time auditory feedback. Four x, y pairs of co-ordinates are derived from the patients affected limb: neck, wrist, elbow and shoulder. A machine learning (ML) platform *Wekinator* (Fiebrink, Trueman, & Cook, 2011) is then used to record, from each patient individually, examples of: i) forward reach movement (target); ii) trunk leaning iii) shoulder abduction and iv) shoulder elevation (three forms of compensatory movement).

To ensure standardization in terms of the extent of each compensatory movement, a goniometer will be used to achieve a standardized maximum for each compensatory movement across all participants. These movements provide *models* which form the basis on which future forward reach movements can be evaluated, allowing the system to determine whether any compensatory movements have occurred above a threshold of 0.2 (this threshold was found to be most effective to give relevant feedback and reduce interference of noise in the system). Compensatory movement above this threshold will result in auditory feedback (muting of the music) until the participant corrects their posture, at which point the music continues and the forward reach movements resume.

Two further *models* will be recorded to give the start position of the target movement and the end point (target position) which will be used to track the total number of repetitions that a patient achieves by counting the number of targets reached. All data is time stamped in *ms* and allows the dependent variable (DV) to be calculated. The DV is a compensation percentage score (i.e. amount of time spent using compensatory movement). Percentage compensation scores will be calculated for each repetition of the target movement and then averaged across blocks for analysis.

4 Participants: recruitment methods, number, age, gender, exclusion/inclusion criteria.

Participants will first be invited to take part in the study by the health professionals working at the Upper Limb Neurorehabilitation Service (ULS) in the National Hospital For Neurology and Neurosurgery (NHNN) either in the clinic or directly on the stroke unit when they start the programme. They will be given information about the study and asked if they would like to be referred to the research team. They will then be put in contact with one of the members of the research team, face to face.

The study will be carried out at the ULS at the NHNN. This means it will be a single site study with attainment of informed consent carried out on site by the Chief Investigator (CI) with support from the Upper Limb team. The four on-site researchers (two physiotherapists and two occupational therapists) will work with the CI to evaluate patient suitability. All patients will be assessed to ensure that if they take part in the study, they will be given individualised forward reach movement patterns that are relevant for their upper limb rehabilitation. We aim to recruit 45 stroke patients for the study.

4.1 Inclusion criteria

Key inclusion criteria include: (1) acceptance on the Upper Limb Neurorehabilitation Service at the NHNN, (2) diagnosis of stroke resulting in hemiparesis at least 6 months prior to study, (3) ability to give informed consent, (4) the cognitive ability to follow the tasks, (5) the ability to lift the affected hand onto a table whilst seated, unaided by their unaffected limb, (6) the ability to sit unsupported for at least 10 minutes, (6) aged between18-75, (7) right-handed, and

(8) inefficiency in their movement pattern that can be tracked by the machine learning system in the study.

4.2 Exclusion criteria

Key exclusion criteria include: (1) absence of stroke diagnosis (2) a high level of functioning in the upper limb (i.e. with little or no further improvement possible), (3) inability to lift affected limb without support.

5 Consent and participant information arrangements, debriefing.

5.1 Patient Information Sheet

Stroke Rehabilitation Research

We would like to invite you to take part in a research study using music and movement.

Participant Information Sheet

Scientific Title of Research: Sonic Sleeve: Reducing Compensatory Movements in Stroke Rehabilitation with the Aid of Auditory Feedback

Name of Chief Investigator: Pedro Douglass Kirk, PhD candidate Goldsmiths University of London.

Education Project: This research will be conducted in part fulfilment of a PhD.

IRAS Project ID Number: 251741

To be registered on ISRCTN when ethical approval obtained

Version 0.1 February 2019

Please take time to carefully read this information sheet and feel free to contact the research team with any questions or concerns you may have. The research team's contact information is at the end of this document.

What is the purpose of the study?
We aim to understand how music can help stroke survivors with their upper limb rehabilitation. The key goal of the research is to see if providing auditory feedback on compensation (such as trunk leaning) can help to promote better movement patterns. Research suggests that if stroke patients can reduce undesirable compensatory movements then they may achieve more consistent and efficient movement patterns.

Why have you been chosen?
You are being invited to take part in this research because your medical team at the Upper Limb Neurorehabilitation Service at the National Hospital For Neurology and Neurosurgery think you would be a good candidate for this study.

Do I have to take part?

Taking part in the study is completely voluntary. Taking part will not affect or interfere with the standard medical care you receive. You may decide to stop being a part of the research study at any time without explanation. You have the right to ask that any data you have supplied to that point be withdrawn or destroyed without penalty.

How long will the study be?
You will need to undertake an assessment with the Upper Limb Team to make sure you can take part in the study with some short follow-up tests. This process will take around 20 minutes to complete. Your involvement in the study would require you to undertake four separate sessions in the upper limb clinic. The four sessions will take around 2 hours 45 minutes over the first few weeks of your three week stay on the upper limb clinic.

1. The first session is to practice and will help familiarize you with the study taken in the first week of your Upper Limb Course
2. The second session will be 45 minutes the day after you finish session 1
3. The third session will last 1 hour and be one week after session 2
4. The final session will last 30 minutes and take place 24 hours after you complete session 3.

What do I have to do?
You will have the assessment with staff as mentioned above followed by some simple tests to make sure you are able to take part in the study. You will also be asked to choose 10 of your favorite pieces of music at the practice session. We will have lots of music and songs to listen to from Spotify (an online streaming service) to help you choose ones that you like.

You will then be required to make some active forward reaching movements while you sit at a table. See the image below - it shows how a participant will sit and move forward to touch a target marked with an X. You will be listening to music while you move. There will be a 2D webcam that sends video to a system we have built for the study to provide feedback on compensatory movements (i.e. trunk leaning).

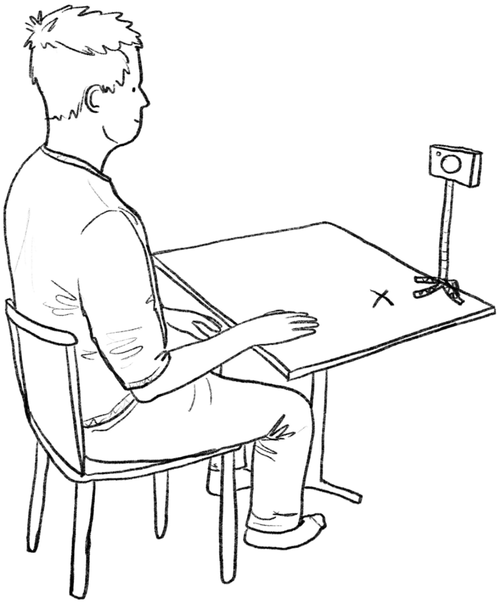


Figure 2: The image shows a patient sitting ready to move forward to the target marked with an X.

There will be a 10 second rest after every 10 movements you make. Then there will be at least two minutes rest after every 50 movements you undertake. You will be able to rest at any time during the session if you feel too tired. Sometimes when you move in the sessions you may receive feedback if you compensate by 1) leaning forward, 2) if your elbow comes out to the side too much or 3) if your shoulder lifts up too much. If this happens the music may stop and you will need to try and get the music to play again.

What are the benefits of taking part in the study?
You may enjoy moving while listening to your favorite music and you may well have a lot of fun taking part in the study. Your participation will help us better understand how music may be helpful in upper limb rehabilitation.

What are the disadvantages and risks of taking part in the study?
There is risk of fatigue due to the physical exercise you will be undertaking. You can rest at any time during the study if you feel too tired. The upper limb team will be available at all times if you require any support. You may also get uncomfortable sitting for long periods of time so you will be able to move around and have a break at any time if you need to.

Will my participation in this study be kept confidential?
All information collected about you during the course of the research will be kept strictly confidential and will be stored on a padlock USB drive which only the research team has access to. None of your personal information will be shared with Goldsmiths, University of London where the student and supervisors are based for this research. If information about your medical history is used in medical or scientific publications no identifying information will be linked to the information. All data will be kept for 5 years and then destroyed.

Once consent has been obtained the original consent form will be stored in the Investigator Site File with one copy stored in your medical notes and one copy given to you (the participant) for reference.

What will happen to the results of the research study?
Following the study, we plan to publish the results in academic/health-based journals and to present our findings at conferences and meetings so that others can learn from the research. We can also provide you with a copy of any published outputs on request.

Who is organising and funding the research?
This research study is being supervised by Professor Lauren Stewart at Goldsmiths, University of London and by Professor Mick Grierson at The Creative Computing Institute. This research study is being conducted by Pedro Douglass-Kirk who is a PhD student at Goldsmiths, University of London as part of an educational qualification. Also members of the Upper Limb team are members of the research for this project. Professor Nick Ward, Fran Brander, Kate Kelly Will Chegwidden and Dhiren Shivji have all helped with setting up the study and will be helping to ensure all patients are undertaking appropriate movements.

Who do I contact?
If you have any questions please ask at any time. You may contact my supervisor or myself:

Pedro Douglass-Kirk	Lauren Stewart
Music, Mind and Brain PhD student	Professor in Psychology
+44 (0)7749551292	+44 (0)20 7919 7195
mu101pk@gold.ac.uk	l.stewart@gold.ac.uk

Thank you for taking the time to read this information sheet.

5.2 Participant Consent Form

PARTICIPANT CONSENT FORM (Sonic Sleeve v0.1)

To confirm that you are willing to participate in the research study, please fill out this form.

If you have any questions please feel free to ask.

	Please initial
1. I confirm that I have read and understood the information sheet provided.	
2. I have had time to consider my participation, ask any questions and they have been answered sufficiently.	
3. I understand that my participation is completely voluntary and I am free to withdraw at any time without reason, without my care being affected.	
4. I am willing to take part in the study by undertaking active forward reaching tasks.	
5. I agree that my GP can be informed of my participation in the research study.	
6. I am willing and able to give the time needed to participate in this study.	
7. I understand that information collected during the study (medical information and movement data) will only be available to the research team and not shared with Goldsmiths University of London. I give permission for the research team to have access to this information.	
8. I give permission for the medical team and the research team to notify each other (with anonymous identifier) if they notice or if there have been any significant changes in my health.	
9. I agree to allow the research team to have my phone number and email and I understand that all my personal information will be kept confidential.	
10. I agree that personal information collected about me can be kept, securely, on Goldsmiths University of London Campus and on a pad locked USB drive.	
11. I acknowledge that I will not be paid a sum of money for taking part in this study.	

Once consent has been obtained the original consent form will be stored in the Investigator Site File with one copy stored in your medical notes and one copy given to you (the participant) for reference.

Participant Signature____

Date______________________

Researcher Signature____

Date______________________

5.3 Participant Debriefing Form

PARTICIPANT DEBRIEF FORM (Sonic Sleeve v0.1)

Scientific Title of Research: Sonic Sleeve: Reducing Compensatory Movements in Stroke Rehabilitation with the Aid of Auditory Feedback

Name of Chief Investigator: Pedro Douglass Kirk, PhD candidate Goldsmiths University of London.

Education Project: This research will be conducted in part fulfilment of a PhD.

IRAS Project ID Number: 251741

To be registered on ISRCTN when ethical approval obtained

Version 0.1 February 2019

We would like to take this opportunity to say **Thank You** for taking the time to take part in our study using music as part of your physical rehabilitation.

Please be assured, all data collected will be treated in the strictest confidence. You are free to withdraw your data from the research at any time by contacting myself Pedro (mu101pk@gold.ac.uk) or my PhD supervisor Prof. Lauren Stewart (l.stewart@gold.ac.uk).

The completed research will help to gain an understanding of how music can aid stroke rehabilitation. If you were unduly or unexpectedly affected by taking part in the study please feel free to feed it back to myself. If you feel unable for whatever reason what-so-ever to talk with me then please either contact my supervisor or any of the health experts at the Upper Limb Service.

Our research has two key hypotheses:

1. Stroke patients undertaking active forward reaching movements while listening to self-selected favourite music will reduce compensatory movements when they receive feedback compared to no feedback.
2. Stroke patients who engage in a training session with this feedback for 200 repetitions will learn to reduce compensation even when this feedback is no longer present. This will be investigated at two time points: immediately after the training phase and 24 hours later.

We are still analysing and writing up the results of the study. If you have any more questions or concerns feel free to contact me via email (mu101pk@gold.ac.uk) or my supervisor Professor Lauren Stewart (l.stewart@gold.ac.uk).

Thank you once again,

Pedro Douglass-Kirk

6 A clear but concise statement of the ethical considerations raised by the project and how you intend to deal with them.

As we are working with stroke patients we will need to be careful to account for possible cognitive and fatigue issues. Screening will be undertaken to assess cognitive ability, fatigue, sustained attention and tiredness. The Montreal Cognitive Assessment (MoCA) and Neurological Fatigue Index (NFI) (taken upon admission to the Upper Limb Programme) will be reviewed. Before each session the patients will fill out the St. Mary's Hospital Sleep Questionnaire (SMH) to assess the previous night's sleep. A six minute test of sustained attention will be undertaken prior to session 1 using the Sustained Attention to Response Task (SART) as detailed by Robertson et al. (1997). Health experts will be on hand to ensure any concerns patients may have are discussed and addressed as soon as they are raised.

7 Estimated start date and duration of project.

The project will start as soon as NHS ethics are cleared. We hope for the start date to be 1/05/2019. The project will then last for 1 year up to 1/05/2020. Each patient will complete the study within the time they spend at the Upper Limb Neurorehabilitation Service at the NHNN (see the study flow chart below for more information).

8 References

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Appendix 5-5 Training Scripts Lab Experiments 1A and 2A

15.1.1 Script for auditory perception

The patient will be sitting in front of a speaker and the CI will play the patient extracts of music and pause the music at various times. The patient is required to respond that they are aware the sound has changed. Providing they are able to achieve this they will move on to try playing with the music once their baseline tempo has been found.

"I am going to play you a short piece of music. The sound may cut out at any time. Please raise your stronger hand if you notice the music cut out."

15.1.2 Script for practice session (baseline tempo)

In the practice session patients will be told the following before they undertake 50 repetitions of movement in blocks of 10. The patient will be set up as described for the target movement sitting with their hands on the table**.** The researcher will then tap into a metronome app the speed of the patient's movements to get a bpm for the speed of movement that will be matched to music tempo.

"Sit up nice and straight. Keep a stable base. Grow tall through the trunk. Keep your bottom against the back of the chair. Keep your shoulders relaxed. Rest your elbow against your waist. Keep both your hands on the edge of the table. Keep your wrists in line with the edge of the table where we have marked [draw hand shapes to give the **start position** on attached paper]. This is the **start position.**

You need to reach forward and touch the button. Then move back to the edge of the table with the hand mark [show hand shape on attached paper] *. This is one movement repetition.*

I will tell you when to start. Keep moving for 5 repetitions. Start moving now at a comfortable pace."

15.1.3 Script for training and calibrating Sonic Sleeve

Patients will hear this script in the practice session to help setup and train the system. As mentioned above (section 4.3 Sonic Sleeve) five models will be trained: three models for compensation and two models for each of the poses in the target movement. There will be 7 key steps to training the system as listed in the short scripts below. Each participant will first undertake 5 repetitions of their optimum movement to reach for the target and this will set a baseline for the three compensatory models (setting the 0.0 thresholds of each model). They will then be asked to provide examples of each compensatory movement in isolation one at a time to record examples (giving the maximum threshold of 1.0). Finally they will provide the start and end poses of the target movement. We will then undertake a brief calibration test to ensure all the models are tracking the compensatory movements and poses. If any of the models are not tracking accurately enough we can record further examples using the appropriate steps below.

1: Setting Individualised Optimum Movement Baseline

"Sit in the ***start position****. We need examples of your best quality movement. [Staff X] will help you move with your best quality. Now do five movement repetitions.*

2: Setting Shoulder Abduction Maximum

"Hold your elbow 15 cm out from your body [measure with tape]. *Hold it there for 5 seconds.* [after hold with support from staff] *Now please relax."*

3: Setting Trunk Leaning Maximum

“Please lean forward 10cm from the back of the chair [measure with tape]. *And hold it there for 5 seconds.* [after hold*] Now please relax.”*

4: Setting Shoulder Elevation Maximum

“Please lift up your shoulder by 5cm to meet my hand [measure with tape]. *And hold it there for 5 seconds.* [after hold] *Now please relax.”*

5: Start Pose

*“Hold the **start position**. Hold this position for 5 seconds.* [after hold] *Now relax.”*

6: Target Pose

“Now hold your hand so that it is touching the button. Hold this position for 5 seconds. [after hold] *Now please relax.”*

7: Calibration

*“Hold the **start position**. Please do five movement repetitions.”*

15.1.4 Script for sessions

Scripts for session 1 - 4 are all similar with all patients in all groups and conditions receiving scripts that tell them how many movements they need to undertake and further if they will receive feedback or not.

Practice script session 1

You need to reach forward and touch the button. Then move back to the edge of the table with the hand mark [show hand shape on attached paper] *. This is one movement repetition.*

You will complete 10 of these movements. Then have a short break of 10 seconds. While you are moving you will hear some music. You may find yourself moving to the beat of the music and that is fine. However, you do not need to move to the music. Don’t worry about keeping in time with the music. The aim is to do 50 repetitions. If you need a rest at any time please just say so.

As you move you might notice that the music stops. This is to let you know you are compensating [show examples]: *for example trunk leaning. Elbow coming out. Shoulder lifting up. You need to get the music playing again. You need to problem-solve. It may be you need to sit up straighter. Or keep your elbow in. Or relax your shoulder.*

“Hold the start position”

[remind the patient if needed] “Sit up nice and straight. Keep a stable base. Grow tall through the trunk. Keep your bottom against the back of the chair. Keep your shoulders relaxed. Rest your elbow against your waist. Keep both your hands on the edge of the table. Keep your wrists in line with the edge of the table. I will tell you when to start. We will be aiming for 50 repetitions.

Always try your best to perform the movements without compensation.

Are you ready? As soon as you hear the music playing you should start reaching forward.”

Phase 1 script session 2

You need to reach forward and touch the button. Then move back to the edge of the table with the hand mark [show hand shape on attached paper] *. This is one movement repetition.*

You will complete 10 of these movements. Then have a short break of 10 seconds. You will complete two separate blocks of 50 repetitions. [show patient the diagram of blocks as the script is read out]*." There is a longer rest of 2 minutes after 50 repetitions.*

Blocks Diagram Phase 1

BLOCK 1

10 reps	**10s**	10 reps	**10s**	10 reps	**10s**	10 reps	**10s**	10 reps	**= 50 reps**

2 mins rest

BLOCK 2

10 reps	**10s**	10 reps	**10s**	10 reps	**10s**	10 reps	**10s**	10 reps	**= 50 reps**

In one of the blocks you might notice that the music stops. This is to let you know you are compensating [show examples]: *for example trunk leaning. Elbow coming out. Shoulder lifting up. You need to get the music playing again. You need to problem-solve. It may be you need to sit up straighter. Or keep your elbow in. Or relax your shoulder.*

In the other block the music will not stop. The order of the blocks is like flipping a coin. So you may start with the feedback or without it.

We are aiming for 100 repetitions in all today. While you are moving you will hear some music. You may find yourself moving to the beat of the music and that is fine. But, you do not need to move to the music. Don't worry about keeping in time with the music. If you need a rest at any time please just say so.

"Hold the start position"

[remind the patient if needed] "Sit up nice and straight. Keep a stable base. Grow tall through the trunk. Keep your bottom against the back of the chair. Keep your shoulders relaxed. Rest your elbow against your waist. Keep both your hands on the edge of the table. Keep your wrists in line with the edge of the table. I will tell you when to start. We will be aiming for 50 repetitions.

Always try your best to perform the movements without compensation.

Are you ready? As soon as you hear the music playing you should start reaching forward."

Phase 2 script session 3

You need to reach forward and touch the button. Then move back to the edge of the table with the hand mark [show hand shape on attached paper] *. This is one movement repetition.*

You will complete 10 of these movements. Then have a short break of 10 seconds. This session we are aiming for 300 repetitions. Resting is really important. [show patient the diagram of blocks as the script is read out]*." There is a longer rest of 2 minutes after 50 repetitions.*

Control Group Only

"You will complete six blocks of 50 repetitions as shown in this diagram here… [show patient the diagram of blocks as the script is read out].

Blocks Diagram Control Group Phase 2

BLOCK 1

10 reps	10s	10 reps	10s	10 reps	10s	10 reps	10s	10 reps	= 50 reps

2 mins rest

BLOCK 2

10 reps	10s	10 reps	10s	10 reps	10s	10 reps	10s	10 reps	= 50 reps

2 mins rest

BLOCK 3

10 reps	10s	10 reps	10s	10 reps	10s	10 reps	10s	10 reps	= 50 reps

2 mins rest

BLOCK 4

10 reps	10s	10 reps	10s	10 reps	10s	10 reps	10s	10 reps	= 50 reps

2 mins rest

BLOCK 5

10 reps	10s	10 reps	10s	10 reps	10s	10 reps	10s	10 reps	= 50 reps

2 mins rest

BLOCK 6

10 reps	10s	10 reps	10s	10 reps	10s	10 reps	10s	10 reps	= 50 reps

You can rest for 2 minutes between each of these blocks. In all six blocks try to perform the reaching movements without compensation [demo live] *such as trunk leaning forward, shoulder lifting up or your elbow coming out like this. You are not going to get any feedback this time (meaning that the music will not cut out if you compensate).”*

Experimental Group Only

“You will complete six blocks of 50 repetitions as shown in this diagram here… [show patient the diagram of blocks as the script is read out].

Blocks Diagram Experimental Group Phase 2

BLOCK 1

10 reps	10s	10 reps	10s	10 reps	10s	10 reps	10s	10 reps	= 50 reps

2 mins rest

BLOCK 2 - 5

10 reps	10s	10 reps	10s	10 reps	10s	10 reps	10s	10 reps	x 4 = 200

2 mins rest

BLOCK 6

10 reps	10s	10 reps	10s	10 reps	10s	10 reps	10s	10 reps	= 50 reps

You can rest for 2 minutes between each of these blocks. In all six blocks try to perform the reaching movements without compensation [demo live] *such as trunk leaning forward, shoulder lifting up or your elbow coming out like this. The first block of 50 repetitions you are not going to get any feedback (meaning that the music will not cut out if you compensate).*

Then in the next 4 blocks you will hear the music cut out if you do any of those compensation movements (this is giving you feedback to try and help you move back to better movement).

You need to get the music playing again. It may be you need to sit up straighter. Or keep your elbow in. Or relax your shoulder.

The final block of 50 repetitions you will not get any feedback.

Both Groups
While you are moving you will hear some music. You may find yourself moving to the beat of the music and that is fine. But, you do not need to move to the music. Don't worry about keeping in time with the music. If you need a rest at any time please just say so.

"Hold the start position"

[remind the patient if needed] "Sit up nice and straight. Keep a stable base. Grow tall through the trunk. Keep your bottom against the back of the chair. Keep your shoulders relaxed. Rest your elbow against your waist. Keep both your hands on the edge of the table. Keep your wrists in line with the edge of the table. I will tell you when to start. We will be aiming for 50 repetitions.

Always try your best to perform the movements without compensation.

Are you ready? As soon as you hear the music playing you should start reaching forward."

Phase 2 script session 4
You need to reach forward and touch the button. Then move back to the edge of the table with the hand mark [show hand shape on attached paper] *. This is one movement repetition.*

You will complete 10 of these movements. Then have a short break of 10 seconds. This session we are aiming for 50 repetitions.

While you are moving you will hear some music. You may find yourself moving to the beat of the music and that is fine. But, you do not need to move to the music. Don't worry about keeping in time with the music. If you need a rest at any time please just say so.

"Hold the start position"

[remind the patient if needed] "Sit up nice and straight. Keep a stable base. Grow tall through the trunk. Keep your bottom against the back of the chair. Keep your shoulders relaxed. Rest your against your waist. Keep both your hands on the edge of the table. Keep your wrists in line with the edge of the table. I will tell you when to start. We will be aiming for 50 repetitions.

Always try your best to perform the movements without compensation.

Are you ready? As soon as you hear the music playing you should start reaching forward."

Appendix 5-6 Visual Aid Printouts Lab Experiments 1A and 2A

15.2.1 Auditory perception

- **Listen** to **music**
- **Music** may cut out
- **Raise** your **stronger hand** if you **notice** the **music cut out**.

15.2.2 Script for practice session

START POSITION

- Sit up nice and **straight**
- Keep a **stable** base
- Grow **tall** through the **trunk**
- Keep your **bottom** against the **back** of the chair
- Keep your **shoulders relaxed**
- Rest your **elbow against** your **waist**
- Keep **both** your **hands** on the **edge** of the **table**
- Keep your **wrists** in line with the **edge** of the **table**

MOVEMENT REPETITION

- **reach forward** and **touch** the **button**
- **move back** to the **hand mark**
- Do **5 repetitions**

15.2.3 Script for training and calibrating Sonic Sleeve

1: Setting Individualised Optimum Movement Baseline

START POSITION

- Sit up nice and **straight**
- Keep a **stable** base
- Grow **tall** through the **trunk**
- Keep your **bottom** against the **back** of the chair
- Keep your **shoulders relaxed**
- Rest your **elbow against** your **waist**
- Keep **both** your **hands** on the **edge** of the **table**
- Keep your **wrists** in line with the **edge** of the **table**

MOVEMENT REPETITION

- **reach forward** and **touch** the **button**
- **move back** to the **hand mark**
- Do **5 repetitions**
- **Relax**

2: Setting Shoulder Abduction Maximum

- Hold your elbow 15 cm out from your body
- Hold it there for 5 seconds
- **Relax**

3: Setting Trunk Leaning Maximum

- Lean forward 10cm from the back of the chair
- Hold it there for 5 seconds
- **Relax**

4: Setting Shoulder Elevation Maximum

- Lift up your shoulder by 5cm
- Hold it there for 5 seconds
- **Relax**

5: Start Pose

Appendix 5-7 NHS Substantial Ethical Amendments

NHS
Health Research Authority

London - Dulwich Research Ethics Committee
Health Research Authority
Skipton House
80 London Road
London
SE1 6LH

Tel: 0207 104 8089

17 September 2020

Mr Pedro Douglass-Kirk
108a Whitehead Building
Goldsmiths University of London
London
SE14 6NW

Dear Mr Douglass-Kirk

Study title:	**Sonic Sleeve: Reducing Compensatory Movements in Stroke Rehabilitation with the Aid of Auditory Feedback**
REC reference:	**19/LO/0579**
Protocol number:	**N/A**
Amendment number:	**Sonic Sleeve Amendment 2 August 17th 2020**
Amendment date:	**17/08/2020**
IRAS project ID:	**251741**

The above amendment was reviewed at the meeting of the Sub-Committee held via correspondence.

Ethical opinion

The members of the Committee taking part in the review gave a favourable ethical opinion of the amendment on the basis described in the notice of amendment form and supporting documentation.

Approved documents

The documents reviewed and approved at the meeting were:

Document	*Version*	*Date*
Completed Amendment Tool [251741_Sonic Sleeve Amendment 2 August 17th 2020_13Aug2020_Locked14Aug20_105921]	V0.1	14 August 2020
Completed Amendment Tool [SONIC_SLEEVE_Amendment_Tool_v1.2_11Jun20]	V0.1	13 August 2020
Covering letter on headed paper [CoveringLetter_v0.2_track_change]	V0.2	14 August 2020
Non-validated questionnaire [Sonic_Sleeve_Questionnaire_HOME_STUDYv_01_Aug13th2020]	V0.1	13 August 2020

Non-validated questionnaire [Sonic_Sleeve_Questionnaire_HOME_STUDYv_01_Aug13th2020.pdf]	V0.1	13 August 2020
Other [flow_chart_v0.3_track_changes.pdf]	V0.3	13 August 2020
Other [substantial_amendment_notification_form]	V0.1	13 August 2020
Participant information sheet (PIS) [SonicSleeve_Information_Sheet_v0.6_track_changes.docx]	v0.6	13 August 2020
Research protocol or project proposal [PROTOCOL_SONIC_SLEEVE_v05_track_changes]	v0.5	13 August 2020

Membership of the Committee

The members of the Committee who took part in the review are listed on the attached sheet.

Working with NHS Care Organisations

Sponsors should ensure that they notify the R&D office for the relevant NHS care organisation of this amendment in line with the terms detailed in the categorisation email issued by the lead nation for the study.

Amendments related to COVID-19

We will update your research summary for the above study on the research summaries section of our website. During this public health emergency, it is vital that everyone can promptly identify all relevant research related to COVID-19 that is taking place globally. If you have not already done so, please register your study on a public registry as soon as possible and provide the HRA with the registration detail, which will be posted alongside other information relating to your project.

Statement of compliance

The Committee is constituted in accordance with the Governance Arrangements for Research Ethics Committees and complies fully with the Standard Operating Procedures for Research Ethics Committees in the UK.

HRA Learning

We are pleased to welcome researchers and research staff to our HRA Learning Events and online learning opportunities– see details at: https://www.hra.nhs.uk/planning-and-improving-research/learning/

IRAS Project ID - 251741: **Please quote this number on all correspondence**

Yours sincerely
PP

[redacted]

Dr Thomas Kabir
Chair

E-mail: dulwich.rec@hra.nhs.uk

London - Dulwich Research Ethics Committee

Attendance at Sub-Committee of the REC meeting via Correspondence

Committee Members:

Name	*Profession*	*Present*	*Notes*
Dr Jiafeng Feng	Research Manager	Yes	
Dr Thomas Kabir	Public Involvement in Research Manager	Yes	

Also in attendance:

Name	*Position (or reason for attending)*
Ms Jade Robinson	Approvals Administrator

Appendix 5-8 Post-Study Questionnaire Home Experiment 1B

To be completed via telephone or video link with the participant.

Patient ID: DATE:	**YES**	**NO**
Do you live alone?	☐	☐
Do you feel comfortable using devices to access the internet?	☐	☐
Where you able to plug in the system without support? ☐ If no who supported you? …………………………………………………………………	☐	☐
Did you need someone in your house to help you use the system? ☐ If yes how many times? ………………………………………………… ☐ Who helped you?…………………………………………………………………………… ☐ What did they help you with? …………………………………………… ………………………………………………………………………………	☐	☐
Did you have enough space to take part in the study comfortably? ☐ If no what were the key issues for you? …………………………………………………………………………………………………… ……………………………………………………………………………………………………	☐	☐
Did you require technical support via phone or video link?	☐	☐
My Internet / Wi-Fi connection was stable during my sessions 1 – Every time, 2 – Mostly, 3 – Frequently, 4 – Occasionally, 5 – Very little	Rating -	
When technical issues arose I could resolve them 1 – Every time, 2 – Mostly, 3 – Frequently, 4 – Occasionally, 5 – Never	Rating -	
Setting up the system in my home was 1 – Very hard, 2 – Hard, 3 – Moderate, 4 – Easy, 5 – Very easy	Rating -	
Using the Sonic Sleeve app was 1 – Very hard, 2 – Hard, 3 – Moderate, 4 – Easy, 5 – Very Easy	Rating -	
I feel that using the sonic sleeve app is beneficial for my rehabilitation 1 – Strongly agree, 2 – Agree, 3 – Neutral , 4 – Disagree, 5 – Strongly disagree	Rating -	

Doing the exercises in the study was physically tiring 1 – Strongly agree, 2 – Agree, 3 – Neutral, 4 – Disagree, 5 – Strongly disagree	Rating -	
I found it hard to concentrate when doing the exercises in the study 1 – Strongly agree, 2 – Agree, 3 – Neutral, 4 – Disagree, 5 – Strongly disagree	Rating -	
The instructions to take part in the study were clear 1 – Strongly agree, 2 – Agree, 3 – Neutral, 4 – Disagree, 5 – Strongly disagree	Rating -	
I enjoyed taking part in the study 1 – Strongly agree, 2 – Agree, 3 – Neutral, 4 – Disagree, 5 – Strongly disagree	Rating -	
Would you like to continue using the Sonic Sleeve app?	☐	☐
Would you recommend the Sonic Sleeve app to other people?	☐	☐
Do you have any other comments?		

Appendix 5-9 Participant Information Sheet Home Experiments 1B and 2B

Stroke Rehabilitation Research

We would like to invite you to take part in a research study using music and movement.

Participant Information Sheet

Scientific Title of Research: Sonic Sleeve: Reducing Compensatory Movements in Stroke Rehabilitation with the Aid of Auditory Feedback

Name of Chief Investigator: Pedro Douglass Kirk, PhD candidate Goldsmiths University of London.

Education Project: This research will be conducted in part fulfilment of a PhD.

IRAS Project ID Number: 251741

ISRTCN trial registration REF: ISRCTN12969079

Ethical approval has been given from London Dulwich REC

Version 0.6 Aug 13th 2020

Please take time to carefully read this information sheet and feel free to contact the research team with any questions or concerns you may have. The research team's contact information is at the end of this document.

What is the purpose of the study?
We aim to understand how music can help stroke survivors with their upper limb rehabilitation. The key goal of the research is to see if providing auditory feedback on compensation (such as trunk leaning) can help to promote better movement patterns. Research suggests that if stroke patients can reduce undesirable compensatory movements then they may achieve more consistent and efficient movement patterns.

Why have you been chosen?
You are being invited to take part in this research because your medical team at the Upper Limb Neurorehabilitation Service at the National Hospital For Neurology and Neurosurgery think you would be a good candidate for this study.

Do I have to take part?
Taking part in the study is completely voluntary. You may decide to stop being a part of the research study at any time without explanation.

How long will the study be?
You will need to undertake an assessment with the Upper Limb Team to make sure you can take part in the study with some short follow-up tests. This process will take around 20 minutes to complete. Your involvement in the study would require you to undertake four separate sessions while you take part in the upper limb programme. The four sessions will take around 2 hours 45 minutes over the four week rehabilitation programme. After you have completed the Upper Limb Programme you have the opportunity to continue with a further 10 sessions over a two week period. The majority of sessions will take place in your own home with support via video link with the staff and researchers.

1. Session 1: to practice and will help familiarize you with the study taken in the first week of your Upper Limb Course
2. Session 2-4: 45 minutes per session and will take place in your home once a week
3. Session 5-14: 1 hour per session and take place over two weeks in your home (one session per day)

What do I have to do?
You will come to a room on the stroke unit for the first session of the study. All following sessions will take place in your home with full support from the staff and research team. Before each session you will fill out the St. Mary's Hospital Sleep Questionnaire to let us know about your sleep quality. And then after each session you will answer a simple question: How tiring did you find taking part in this session? [Not at all, a little, rather, very, extremely]. The initial assessment with staff as mentioned above (session 1) will be completed first followed by some simple tests to make sure you can take part in the study. You will also be asked to choose 10 of your favorite pieces of music at the practice session. We will have lots of music and songs to listen to from Spotify (an online streaming service) to help you choose ones that you like. The music you choose will be used in sessions 2-14 and not in the practice session 1.

You will be listening to music while you move. There will be a Microsoft Camera that sends video to a system we have built for the study to provide feedback on compensatory movements such as trunk leaning (leaning forward). You will need to do some basic movements to help train the system to track your movements. The training requires you to move your hand from a start position with your wrist on the edge of a table forward to a button marked with an X five times (see image below). You will need to sit up nice and straight with your shoulders relaxed and elbow in towards your body. After this you will need to hold three positions for 5 seconds at a time set by a health expert: 1) hold your affected elbow out at an angle, 2) lean forward by a certain amount and 3) lift up your affected shoulder by a certain amount. After this, you will need to hold your hand on the edge of the table at the start position for 5 seconds, then move your hand forward to the button and hold it there for 5 seconds. This will complete the training sequence.

As part of the first practice session, you will then be required to make some active forward-reaching movements while you sit at a table. See the image below - it shows how a participant will sit and move forward to touch a button. You need to move forward and back five times at a comfortable speed for us to set the speed of your movements. We will then select some music that matches your natural pace.

You will then move along to the music as a practice to get familiar with the setup for 50 repetitions. There will be a 10 second rest after every 10 movements you make. Then there will be at least two minutes rest after every 50 movements you undertake. You will be able to rest at any time during the session if you feel too tired. Sometimes when you move in the sessions you may receive feedback if you compensate by 1) leaning forward, 2) if your elbow comes out to the side too much or 3) if your shoulder lifts up too much. If you compensate the music may stop and you will need to try and get the music to play again by relaxing back into a good posture with your back straight and elbow in. After this first practice session is over there will be two phases to the main study. After all sessions, you will be asked to fill out a rating of how tired you feel.

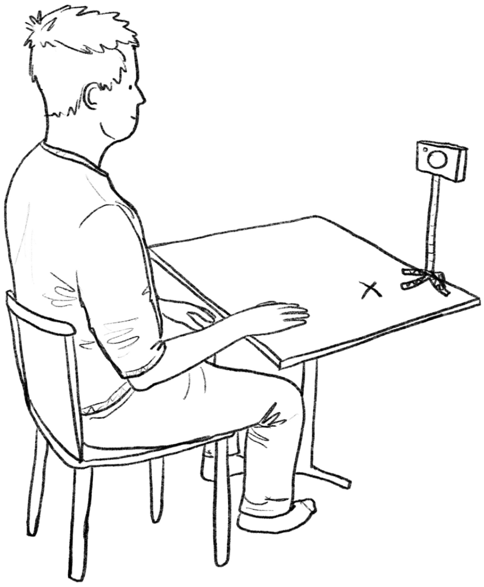

Figure 2: The image shows a patient sitting ready to move forward to a button marked with an X.

Phase 1:
Session 2 will take place in your home, and we will check that the system is working as it did in the practice session by doing the same movement reaching to the button 5 times. Then you will undertake two blocks of 50 repetitions with a 2-minute break between the blocks and a 10 second rest every 10 repetitions. You will be moving to the music you selected in the practice session. In one of the blocks you will hear the music cut out if you use compensation (such as trunk leaning, elbow coming out or shoulder lifting up) providing feedback to help you move back to a more optimal movement. In the other block you won't get the feedback. The order of the blocks is like flipping a coin. So you may start with the feedback or without it. In both blocks you need to try and move without compensating. You will repeat this same procedure each week (3 times in total) while you are on the upper limb course.

Phase 2:
A week after phase 1 is finished you will be invited to take part for session 5. You will undertake 300 repetitions moving to your favourite self chosen music split into 6 blocks of 50 repetitions. You will

be randomised into either an active group where you will receive feedback in some of the movement blocks or a control group where you will not receive feedback in any of the blocks.

The randomisation process will use a random number generator common in psychology research (https://www.randomizer.org/#randomize). Both groups will undertake the 300 repetitions with 10 second rests every 10 repetitions and a 2-minute rest every 50 repetitions. If you are in the active group you will undertake the first and final bock of 50 repetitions without any feedback. During the middle 4 blocks of 200 repetitions you will receive feedback in the active group. This process is then repeated for two weeks once a day Monday to Friday up to a total of 10 sessions.

Finally you will be asked to complete a short questionnaire via telephone or video link after you have completed the study.

What are the benefits of taking part in the study?
You may enjoy moving while listening to your favorite music. Your participation will help us better understand how music may be helpful in upper limb rehabilitation.

What are the disadvantages and risks of taking part in the study?
There is risk of fatigue due to the physical exercise you will be undertaking. You can rest at any time during the study if you feel too tired. The upper limb team will be available at all times if you require any support via our secure video setup used for your rehabilitation. You may also get uncomfortable sitting for long periods of time so you will be able to move around and have a break at any time if you need to.

Will my participation in this study be kept confidential?
All information collected about you during the course of the research will be kept strictly confidential and will be stored on secure University servers.

Goldsmiths University of London is the sponsor for this study based in the United Kingdom. We will be using information from you and your medical records in order to undertake this study and will act as the data controller for this study. This means that we are responsible for looking after your information and using it properly. Goldsmiths University of London will keep identifiable information about you for 5 years after the study has finished.

Your rights to access, change or move your information are limited, as we need to manage your information in specific ways in order for the research to be reliable and accurate. If you withdraw from the study, we will keep the information about you that we have already obtained. To safeguard your rights, we will use the minimum personally-identifiable information possible.

You can find out more about how we use your information by contacting the Chief Investigator Pedro Douglass-Kirk via email mu101pk@gold.ac.uk.

The research team on the NHS upper limb programme will use your name, NHS number and contact details to contact you about the research study, and make sure that relevant information about the study is recorded for your care, and to oversee the quality of the study. Individuals from Goldsmiths University of London and regulatory organisations may look at your medical and research records to check the accuracy of the research study. The NHS upper limb service will pass these details to Goldsmiths University of London along with the information collected from you and your medical records. The only people in Goldsmiths University of London who will have access to information that identifies you will be people who need to contact you to follow-up with you or audit the data collection process. The people who analyse the information will not be able to identify you and will not be able to find out your name, NHS number or contact details. The NHS upper limb service will keep identifiable information about you from this study for 5 years after the study has finished.

Goldsmiths University of London will collect information about you for this research study from the NHS upper limb service. This information will include your name, NHS number, contact details and health information. Further demographic information will also be collected including age, SES (annual income), ethnicity, marital status (married, partner or single), occupation, education, medication, contact information (phone number and email), details of your stroke, and lifestyle information, which is regarded as a special category of information. We will use this information to help with our interpretation of results. If information about your medical history is used in medical or scientific publications no identifying information will be linked to the information. All data will be kept for 5 years and then destroyed. Once consent has been obtained the original consent form will be stored in the Investigator Site File with one copy stored in your medical notes and one copy given to you for reference.

Are there any differences compared to standard care?
Standard care on the upper limb service is an intensive programme where you will need to do physical activities for 6 hours per day five days a week for four full weeks. There will be a whole range of physical exercises and goal setting you will undertake on the upper limb service that you will have discussed during your clinic session with medical staff. There will be no travel costs associated with the study as you will be on the stroke unit as part of your standard care or in your own home.

Taking part in the study will differ to the standard care you would get on the upper limb service in a number of ways. Firstly, you will be required to have the short assessment with the medical staff and some basic screening tests with a researcher to make sure you can take part in the study.

Secondly, you will be required to fill out two short questionnaires at each session that are not part of standard care. Before each session you will fill out the St. Mary's Hospital Sleep Questionnaire to let us know about your sleep quality. And then after each session you will answer a simple question: How tiring did you find taking part in this session? [Not at all, a little, rather, very, extremely].

Thirdly, you will be undertaking the forward-reaching exercises in the research that may be a little different from some of the other exercises on the upper limb programme where you work with physiotherapists and occupational therapists. The staff will ensure that the exercises you do in the study are relevant for your upper limb programme. The study sessions will become part of your timetable. There are 4 sessions over the three weeks you are on the upper limb course as stated above that will take approximately 2 hours 45 minutes to complete.

What will happen to the results of the research study?
Following the study, we plan to publish the results in academic/health-based journals and to present our findings at conferences and meetings so that others can learn from the research. We can also provide you with a copy of any published outputs on request.

As a university in collaboration with the NHS upper limb service, we use personally-identifiable information to conduct research to improve health, care and services. As a publicly-funded organisation, we have to ensure that it is in the public interest when we use personally-identifiable information from people who have agreed to take part in research. This means that when you agree to take part in a research study, we will use your data in the ways needed to conduct and analyse the research study. Your rights to access, change or move your information are limited, as we need to manage your information in specific ways in order for the research to be reliable and accurate. If you withdraw from the study, we will keep the information about you that we have already obtained. To safeguard your rights, we will use the minimum personally-identifiable information possible.

Health and care research should serve the public interest, which means that we have to demonstrate that our research serves the interests of society as a whole. We do this by following the UK Policy Framework for Health and Social Care Research.

Who is organising and funding the research?

This research study is being supervised by Professor Lauren Stewart at Goldsmiths, University of London and by Professor Mick Grierson at The Creative Computing Institute. This research study is being conducted by Pedro Douglass-Kirk who is a PhD student at Goldsmiths, University of London as part of an educational qualification. Also members of the Upper Limb team are members of the research for this project. Professor Nick Ward, Fran Brander, Kate Kelly, Will Chegwidden and Dhiren Shivji have all helped with setting up the study and will be helping to ensure all patients are undertaking appropriate movements.

Who do I contact?

If you have any questions please ask at any time. You may contact my supervisor or myself:

Pedro Douglass-Kirk	**Lauren Stewart**
Music, Mind and Brain PhD student	Professor in Psychology
07749551292	020 7919 7195
mu101pk@gold.ac.uk	l.stewart@gold.ac.uk

Who do I contact if I have a complaint?

If you wish to raise a complaint on how we have handled your personal data, you can contact our Data Protection Officer who will investigate the matter. If you are not satisfied with our response or believe we are processing your personal data in a way that is not lawful you can complain to the Information Commissioner's Office (ICO) via their website (https://ico.org.uk) or call them on 0303 123 1113. Our Data Protection Officer is Matthew Ramsey and you can contact him via email dp@gold.ac.uk or call 02079 197 171. If you are not satisfied with your hospital experience please speak to the person in charge of the ward or clinic. In this case you can contact Professor Nick Ward: Tel: 020 3448 3924 Email: n.ward@ucl.ac.uk

We are keen to ensure the highest standards of patient care and will try to resolve any problems quickly. You can also speak to our Patient Advice and Liaison Service (PALS) who will help with your problem quickly and informally. Contact PALS on 020 3447 3042.
If you are still not satisfied you can make a formal complaint. This will not affect your hospital treatment in any way.

To make a formal complaint to UCLH

You can do this within 12 months of the events concerned, or within 12 months of becoming aware of the problem. Your complaint will be recorded as part of our formal complaints policy. Please write with full details to the Chief Executive (details above) or to the Complaints Manager at:
Quality and Safety Department, UCLH
2nd Floor West
250 Euston Road
London
NW1 2PG
Telephone: 020 3447 7413
Email: uclh.complaints@nhs.net

Thank you for taking the time to read this information sheet.

Thesis END