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Rhythmic Haptic Cueing for Gait Rehabilitation of Hemiparetic Stroke and Brain Injury Survivors

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

July 2018

Abstract

This thesis explores the gait rehabilitation of hemiparetic stroke and brain injury survivors by a process of haptic entrainment to rhythmic cues.

Entrainment to auditory metronomes is known to improve gait; this thesis presents the first systematic study of entrainment for gait rehabilitation via the haptic modality.

To investigate this approach, a multi-limb metronome capable of delivering a steady, isochronous haptic rhythm to alternating legs was developed, purpose-built for gait rehabilitation, together with appropriate software for monitoring and assessing gait.

A formative observational study, carried out at a specialised neurological centre, supplemented by discussions with physiotherapists and neuropsychologists, was used to focus the scope on hemiparetic stroke and brain injury. A second formative study used a technology probe approach to explore the behaviour of hemiparetic participants under haptic cueing using a pre-existing prototype. Qualitative data was collected by observation of, and discussion with, participants and health professionals.

In preparation for a quantitative gait study, a formal experiment was carried out to identify a workable range for haptic entrainment. This led to the creation of a procedure to screen out those with cognitive difficulties entraining to a rhythm, regardless of their walking ability.

The final study was a quantitative gait study combining temporal and spatial data on haptically cued participants with hemiparetic stroke and brain injury. Gait characteristics were measured before, during and after cueing. All successfully screened participants were able to synchronise their steps to a haptically presented rhythm. For a substantial proportion of participants, an immediate (though not necessarily lasting) improvement of temporal gait characteristics was found during cueing. Some improvements over baseline occurred immediately afterwards, rather than during, haptic cueing.

Design issues and trade-offs are identified, and interactions between perception, sensory deficit, attention, memory, cognitive load and haptic entrainment are noted.

Author's declaration

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-Theodoros Georgiou

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Published work

The work presented in this thesis has led to the following publications, in chronological order.

- Georgiou, T. et al., 2015. A blended user centred design study for wearable haptic gait rehabilitation following hemiparetic stroke. In *9th International Conference on Pervasive Computing Technologies for Healthcare*. Istanbul, Turkey. URL: <http://oro.open.ac.uk/42593/>
- Georgiou, T., Holland, S. & Linden, J. van der, 2016. Rhythmic Haptic Cueing for Entrainment: Assisting Post-Stroke Gait Rehabilitation. In *Designing Around People*. Cambridge: Springer International Publishing, pp. 55–64. URL: <http://oro.open.ac.uk/45150/>
- Georgiou, T., Holland, S. & van der Linden, J., 2016. Wearable Haptic Devices For Post-Stroke Gait Rehabilitation. In *International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct*. Heidelberg. URL: <http://oro.open.ac.uk/47000/>
- Georgiou, T., Holland, S., Linden, J. van der, et al., 2017. Questioning Classic Patient Classification Techniques in Gait Rehabilitation: Insights from Wearable Haptic Technology. In K. Giokas, L. Bokor, & F. Hopfgartner, eds. *eHealth 360: International Summit on eHealth, Budapest, Hungary, June 14-16, 2016, Revised Selected Papers*. Cham: Springer International Publishing, pp. 327–339. URL: <http://oro.open.ac.uk/46336/>
- Georgiou, T., Holland, S., van der Linden, J., 2017. Two kinds of entrainment in gait rehabilitation using haptic metronomic cues. *16th Rhythm Production and Perception Workshop*, 257(3), pp.6–7. URL: <http://oro.open.ac.uk/48900/>

Visi, F., Georgiou, T., Holland, S., Pinzone, O., Donaldson, G., and Tetley, J., 2017. Assessing the Accuracy of an Algorithm for the Estimation of Spatial Gait Parameters Using Inertial Measurement Units: Application to Healthy Subject and Hemiparetic Stroke Survivor. *4th International Conference on Movement Computing*. London.
URL: <http://oro.open.ac.uk/49866/>

Posters:

Georgiou, T., Holland, S., van der Linden, J., 2016. Rhythmic haptic cueing for gait rehabilitation of neurological conditions. 30th International BCS Human Computer Interaction Conference: Fusion!, Bournemouth.
URL: dl.acm.org/citation.cfm?id=3056358

Georgiou, T., Holland, S., van der Linden, J., et al. 2017. Rhythm and Gait rehabilitation: a case study using rhythmic haptic cueing for stabilising gait and improving asymmetries. *26th European Stroke Conference*. Berlin, Germany. URL: <http://oro.open.ac.uk/49028/>

Demonstrations:

Georgiou, T., Holland, S., van der Linden, J., 2016. The Haptic Bracelets: Gait rehabilitation after stroke. EuroHaptics 2016. London.
URL: <http://oro.open.ac.uk/46434/>

Collaboration agreements and Ethics

The observation sessions (Chapter 4) were carried out under a collaboration agreement between The Open University and P J Care LTD. More specifically, Eagle Wood, a P J Care Home in Peterborough specialising in neurological conditions, signed a written agreement of collaboration in carrying out observation, dialogue, participative demonstrations and trials with staff and residents at Eagle Wood.

Favourable ethical opinion was granted by the Open University Human Research Ethics Committee and the Manchester Metropolitan University Ethics Committee for all relevant studies. All studies were carried out in accordance with the principles laid down by the Declaration of Helsinki.

The ethics approval reference numbers are:

- Technology probe study (Chapter 4).
 - HREC/2014/1861/Georgiou/1
 - MMU ethics reference number 1263
- Haptic Rhythm Perception test (Chapter 6).
 - HREC/2015/2088/Georgiou/1
- Entrainment to rhythmic haptic cues for gait rehabilitation (Chapter 7)
 - HREC/2015/2551/Georgiou/1
 - MMU ethics reference number 1368

See Appendix 1 (page 173) for the collaboration agreement document and ethics approval forms.

List of Collaborators

Even though this thesis represents my own work, several people contributed by offering their practical and technical expertise. These people and their contribution are named below:

The Open University

Dr Federico Visi – *Research Assistant at the Music Computing Lab.*

Offered a helping hand during the study discussed in Chapter 7, and provided his technical experience when working with a Qualisys optical motion capture system. Dr Visi also used data collected from this study to validate a prototype algorithm we designed for calculating step lengths from wearable motion sensors worn on the shank of the leg.

Manchester Metropolitan University (MMU)

Professor Josephine Tetley – *Professor of Nursing.*

Mrs Glenis Donaldson – *Senior lecturer and clinical gait analyst.*

Mrs Ornella Pinzone – *Clinical gait analyst and kinematics technician.*

Collaborators from the Manchester Metropolitan University (MMU) assisted during the participant recruitment process and provided access to a specialised kinematics lab fitted with a Qualisys optical motion capture system. The team from MMU also assisted in capturing data from the Qualisys motion capture system that were used for triangulation of data purposes, and provided valuable insights and expert reviews during the studies discussed in Chapter 4 (section 4.2) and Chapter 7. Professor Tetley, Mrs Donaldson, and Mrs Pinzone are co-authors in four publications (one poster) from this research.

University of Warwick

Dr Mark Elliott – *Assistant Professor, Institute of Digital Healthcare.*

Dr Elliott provided vital insights during the design of the tap test used for the study discussed in Chapter 6. Dr Elliott also helped with the design of the bespoke algorithms used for analysing the data from the tap test (Chapter 6) by sharing a Matlab script (MatTAP (Elliott, Welchman and Wing, 2009)) he previously developed for matching events with responses.

University of Birmingham

Dr Roberta Roberts – *Research Fellow*.

Dr Roberts assisted with the analysis of the data obtained from the study in Chapter 6. Specifically, she provided her expertise during the data analysis and helped with the correct interpretation of the data gathered from this study.

Private specialist physiotherapists and health professionals

Dr Allan Perry – *Consultant Clinical Neuropsychologist* (P J Care).

Siôn and Pamela – *Resident physiotherapists* (P J Care).

Rachel Canning – *Specialist physiotherapist* (Private practice).

Dr Allan, Siôn, Pamela, and Rachel, are all experienced health professionals specialising in therapy and physiotherapy of people suffering from neurological conditions. Their assistance was crucial during the observation session in the formative study discussed in Chapter 4.

Dr Allan Perry, Siôn, and Pamela helped me acquire crucial insights on current gait rehabilitation techniques and helped me understand various neurological conditions, how they affect individuals, and why each rehabilitation exercise is important, both for the physical, and mental status of the patient. These insights are discussed in detail in Chapter 4.

Mrs Canning helped with the participant recruitment process for the study presented in Chapter 7 and retrospectively commented on their progress after the study took place.

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Figures disclaimer

All but the following figures have been created by the author.

Figure 2

Left: Cut from the engraving following the painting of Caspar Netscher by G. Edelinck, between 1684 and 1687. Image source:

https://commons.wikimedia.org/wiki/File:Christiaan_Huygens.gif

Right: Drawing of the first pendulum clock, designed by Dutch scientist Christiaan Huygens in 1657. Image source:

https://commons.wikimedia.org/wiki/File:Huygens_first_pendulum_clock_-_front_view.png

Figure 3

Image created by a composition of images. The human outline is under CC0 creative commons license marked as “Free for commercial use. No attribution required”. Image source: <https://pixabay.com/en/man-tourist-holding-bag-briefcase-1598067/>

The smartphone outline is under Creative Commons Attribution 3.0 Unported. The image was originally created by Designmodo. Image source:

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Figure 4

Image created using parts of one image. The original image is under CC0 creative commons license marked as “Free for commercial use. No attribution required”. Image source: <https://www.pixcove.com/man-gentleman-humanoid-silhouette-outline-human-walking/>

Figure 5

Image on the left taken from manufacturer's official website: <https://cdn-content.qualisys.com/2014/01/gait-setup-3d-1200x675.jpg>

Figure 6

Images taken from manufacturer's official website:

<https://www.zebris.de/en/medical/products-solutions/stance-gait-and-roll-off-analysis-fdm/>

Figure 7

Images taken from manufacturers' official websites.

Left image: <https://www.fitbit.com/uk/home>

Right image: <https://www.apple.com/uk/watch/>

Figure 8

Images taken from manufacturer's official website:
<http://www.gaitsmart.com/human-analysis>

Figure 16 and Figure 17

Images used with permission of the 'Music Computing Lab' at 'The Open University'. Link: <http://mcl.open.ac.uk/MusicLab>

Figure 35

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Figure 52

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Tape measure icon created by Musket. Image source:
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Chapter 1

Introduction

Rhythm, brain and the body are closely linked. Humans can synchronise their movement to auditory rhythms with little apparent effort (Zatorre, Chen and Penhune, 2007). This is demonstrated through the widespread inclination to spontaneously move to music, either by tapping, nodding, or in more committed cases, dancing. The ability to extract meaningful temporal structure from incoming sensory stimuli forms the basis of many human activities, from holding a conversation to playing music.

However, the ability to perform rhythmic movement can be severely disrupted due to neurological conditions. Even in cases where the ability to perceive rhythms remain, a neurological condition may affect the mechanisms controlling the muscles during movement. Arguably, the most important voluntarily controlled rhythmic movement in the human body is walking, as it is linked to independence and higher quality of life. Having the gait rhythm disrupted brings severe asymmetries between steps, which lead to numerous physical problems – ranging from muscle degeneration to bone fractures – accentuating the patient's condition.

This thesis focuses on patients suffering from *hemiparesis* – a neurological conditions affecting one side of the body unilaterally. Hemiparesis is the most common source of adult disability and is usually caused by brain trauma or injury to the brain such as stroke (Roger *et al.*, 2011; Wasay, Khatri and Kaul, 2014; Stroke Association, 2017).

Utilising the ability to perceive rhythm and trying to synchronise steps to the beats of an audio rhythm has shown significant benefits to the way a person suffering from a neurological condition walks, stabilising their disrupted gait pattern and improving any asymmetries (discussed in Chapter 2, page 27).

Interestingly, the phenomenon where rhythmic processes synchronise to each other was first defined in the field of physics and mathematics after observations made in the 17th century on mechanical oscillations (Strogatz and Stewart, 1993). Independent mechanical oscillators – under certain conditions – would synchronise to each other in a process known as *entrainment*. It was not until a quarter of a millennium later the potential of this observation was realised in the area of physiotherapy and rehabilitation, and used for stabilising and improving gait asymmetries of neurological conditions such as hemiparesis (Thaut *et al.*, 1993). Use of a constant rhythm provided by a metronome has been investigated and successfully demonstrated as a means of improving hemiparetic gait with immediate effects (Thaut *et al.*, 2007). The neurological enhancement of gait is mediated by a rhythmic entrainment effect in which the external rhythm acts as a timekeeper, entraining desired movement frequencies and retraining motor programs by precisely choreographing muscle activation patterns (Thaut, 2007). Walking to an audio rhythm was found to offer greater benefits in a much shorter time period than more traditional gait rehabilitation methods (Thaut *et al.*, 2007).

However, there are circumstances where audio cues may be undesirable or unsuitable, as discussed on section 2.7.2 (page 36), for example when wishing to maintain full environmental awareness or social engagement. In addition, with audio cues alone, it is difficult to differentiate which cue is for which leg (Wright *et al.*, 2013), thus missing out on some potentially beneficial aspects of focusing attention and proprioception in gait rehabilitation. In contrast, the sense of touch, through haptic cues, is a promising potential alternative.

This thesis explores the role of rhythmic cues delivered via the haptic modality in what is the first systematic exploration of the haptic sense as a sole source of rhythm aiming at motor synchronisation via entrainment in the context of gait rehabilitation.

1.1 Aim of this thesis

This thesis addresses the following research question.

How can entrainment through rhythmic haptic cueing assist with gait rehabilitation of neurological conditions?

The question is motivated by empirical and theoretical evidence, rooted in the literature, indicating that walking to an audio rhythm is a promising approach of assisting gait rehabilitation, with significant benefits to neurological conditions. The approach adopted in this thesis is fourfold:

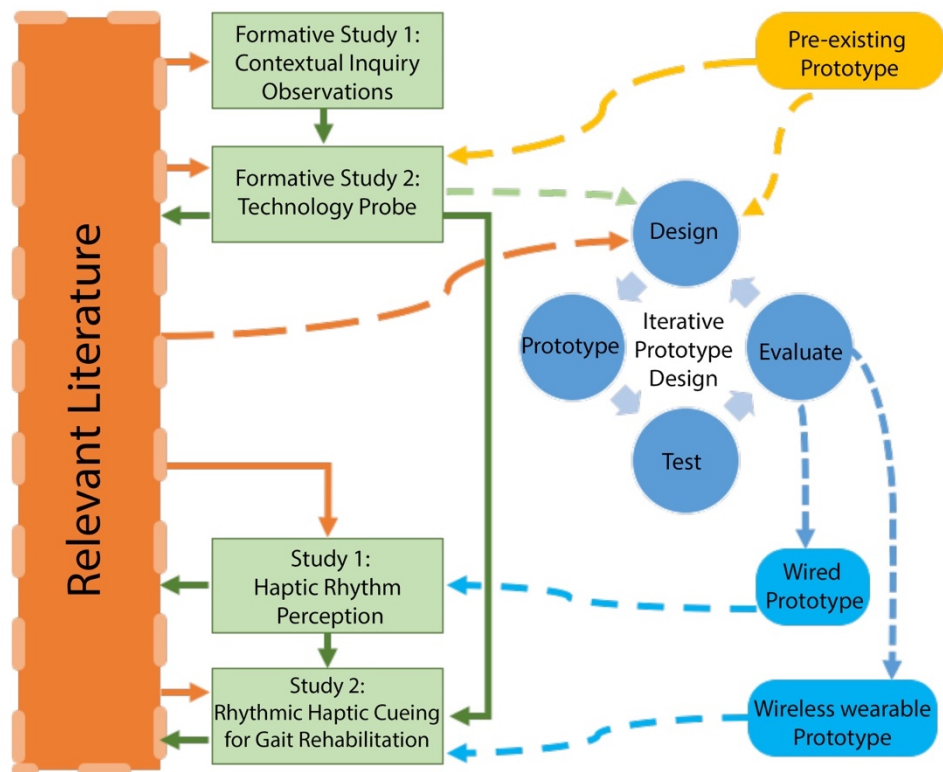
- to investigate the needs of patients and health practitioners in connection with the technology;
- to iteratively design and develop the technologies necessary to mediate the desired haptic rhythm;
- to design and develop the gait monitoring and analysis tools necessary for assessing patients' gait, quantifying the effects and benefits, leading to an evaluation and efficacy of rhythmic haptic cueing in assisting gait rehabilitation;
- to investigate the effects of entrainment between rhythmic haptic cueing and people's gait within the context of gait rehabilitation, looking for both immediate and lasting effects and benefits.

1.1.1 Research question in more detail

For maximum generality, the research question, as initially phrased, makes no mention of specific neurological conditions. However, in some later parts of

Section 1.2 on the next page presents a roadmap of this research and section 1.3 provides an overview of this thesis, but in summary, the thesis' aim was to explore the role of rhythmic haptic cueing in the context of gait rehabilitation, focusing on patients suffering from chronic hemiparesis caused by brain injury or stroke.

1.2 Research roadmap



pg. 4

The roadmap of this research is summarised in Figure 1 above. The ***first formative study*** applied user-centred design methods, including a form of contextual inquiry, to gain insights into current rehabilitation techniques for neurological conditions. Findings from this exploratory study influenced directly the design of the ***second formative study***, which used a technology probe to investigate what both patients and physiotherapists needed from the technology, and to gain a first understanding of the efficacy of rhythmic haptic cueing as an aid for gait rehabilitation. For this study, a ***pre-existing prototype*** was used (see Chapter 5). The findings from both formative studies, the pre-existing prototype design, and knowledge from the relevant literature, all influenced the beginning of an ***iterative prototype design*** process that would continue throughout this research, producing two prototype devices – one wired and one wireless– used in the two subsequent studies. Each prototype device addressed different aspects explored in the user studies discussed in Chapters 6 and 7.

1.3 Chapter overview

The subsequent chapters of this thesis are structured as follows.

- Chapter 2 provides a critical survey of the literature focusing on rhythm, rhythm perception, and its application to gait rehabilitation.
- Chapter 3 presents the methodology used for collecting and analysing data in the studies presented in this thesis.
- Chapter 4 presents two formative studies. The first study critically reviewed a series of observations made at a specialised residential neurological centre. Observations were made of: the views of physiotherapists and a consultant neuropsychologist; the gait patterns of various residents; and current gait rehabilitation techniques employed at the centre. These observations helped to narrow down subsequent parts

of the research to a specific neurological condition, namely hemiparesis following stroke and brain trauma.

The second formative study in this chapter involved sessions in which hemiparetic participants were provided with rhythmic haptic cues using a pre-existing prototype. Data was collected during these sessions from three sources: observations, open-ended discussions with participants, and consultation with physiotherapists. The work in this chapter fed into the design of a new prototype wearable wireless haptic device, described in the next chapter.

- Chapter 5 describes the hardware and software designed and developed for use in the study described in Chapter 7. The design of this system was based on observations and insights gathered from the formative studies discussed in Chapter 4 and findings from the literature discussed in Chapter 2.
- Chapter 6 contains a study aiming to address a gap identified in the literature which concerns the ability of humans to synchronise their movement (or entrain) to haptic rhythms.
- Chapter 7 discusses a study aiming to investigate and quantify the effects of rhythmic haptic cueing to the gait patterns of hemiparetic stroke and brain injury survivors.
- Chapter 8 summarises the findings and suggests future research in rhythmic haptic cueing as an aid to support gait rehabilitation of neurological conditions.

Chapter 2

Literature review

Rhythm plays an important role throughout this thesis. This is an aspect of the research that involves somewhat different theoretical perspectives from most research in haptics and haptic perception. Therefore, this chapter starts by considering *rhythm* and how it is perceived in the brain, before moving on to consider how rhythm can affect movement, in the context of gait rehabilitation. The chapter concludes with findings from the literature on gait rehabilitation using auditory rhythms, before introducing the novel approach this thesis proposes of gait rehabilitation using *rhythmic haptic cues*.

2.1 Music and rhythm

Music can be found throughout human history and in all cultures and societies (Wallin, Brown and Merker, 2000). Music is used as a medium to express ideas, emotions and feelings and as a means of bringing people together and structuring their interactions. These interactions can vary from just listening to music performances, to singing or producing music together, moving or dancing to music, and sharing rituals and experiences accompanied and enhanced by music (Thaut, 2007).

Music is a complex phenomenon with rhythm being one of the core elements (White, 1984). In a musical context, the term ‘rhythm’ refers to a potentially complex and multi-dimensional phenomenon, the systematic patterning of sound in terms of timing, accent, and grouping (Patel, 2008). However, in this thesis, the term ‘rhythm’ will be used exclusively to refer to something

simpler, namely what is known technically as an ‘isochronous rhythm’. An isochronous rhythm is series of regular, completely evenly spaced beats. Furthermore, it will be assumed in this thesis that each beat is of the same intensity. The time between each beat is called the ‘period’. When considering a sequence of beats, it is often convenient to talk about the tempo. Tempo refers to the number of beats per minute and is often described as the speed of the rhythm (i.e. more beats per minute means a higher tempo, hence a faster rhythm).

The section below describes how rhythm is perceived, and the underlying neurological mechanisms that allow synchronisation between rhythm perception and motor control mechanisms; something that is crucial for gait rehabilitation of people with neurological conditions and gait deficiencies.

2.2 Moving to the rhythm – entrainment

Rhythm can be used to synchronise motor movement of the lower limbs into stable relationships contributing to more healthy walking patterns (discussed in detail in section 2.2.3). The next section offers a brief account of the history of *entrainment*, a natural phenomenon where two (or more) rhythmic processes interact with each other until they adjust to a common rhythm, before proceeding on how it can be employed to assist patients during movement rehabilitation.

2.2.1 History of entrainment

Entrainment was formally described in the 17th century, after a Dutch mathematician and scientist, Christiaan Huygens, invented the pendulum clock. Huygens noticed that when two pendulum clocks were placed on a common flexible support (in Huygens case a wooden mantelpiece), the motion of the pendulums would synchronise with each other. Even when he nudged the pendulum of one clock out of synchronisation, they would regain perfect synchrony within half an hour (Ancona and Chong, 1999). He suspected that

the two clocks were influencing each other through tiny vibrations in their common support, the wooden beam. In order to test this, he moved them to opposite sides of the room, and sure enough, the clocks fell out of step. Therefore, a link was needed between the two clocks and the common support beam was that link. What Huygens observed was what we now call ‘coupled oscillations’, or *entrainment*.

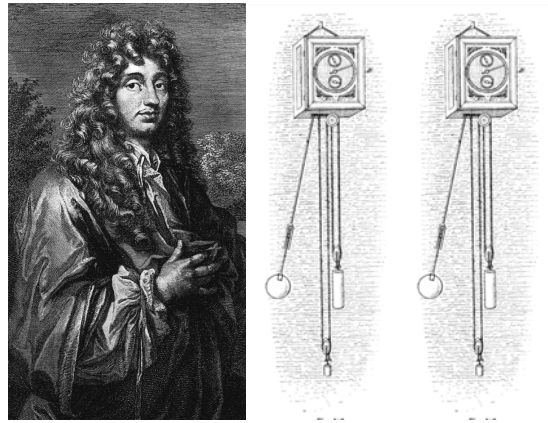


Figure 2 Christiaan Huygens (1629-1695). He was the first to describe the natural phenomenon of entrainment, after inventing the pendulum clock.

The section below considers how entrainment is defined in physics, and the conditions that makes entrainment possible, before moving on to how this relates to biological entrainment, and how external rhythmic stimuli can be used to stabilise gait patterns for rehabilitation.

2.2.2 Entrainment in physics

Entrainment is defined as “a process whereby two rhythmic processes interact with each other in such a way that they adjust towards, and eventually ‘lock in’, to a common phase and/or periodicity” (Clayton, Sager and Will, 2005).

In physics, entrainment is defined as the effects one harmonic oscillator has on the motion of a second nearby (or coupled) oscillator operated at a similar frequency (the meaning of ‘similar’ in this context is explored later). More specifically, entrainment is the process where two oscillating bodies, which

have different periods when they function independently, assume a common or related period (Clayton, Sager and Will, 2005).

In order for entrainment to take place, the following two conditions must be satisfied (Clayton, Sager and Will, 2005):

- a) **Two or more autonomous rhythmic processes or oscillators must exist.** All oscillators in the system must be able to oscillate *on their own*, even if they do not interact with each other. Therefore, all oscillators must have an internal source of energy and not depend on the interaction for producing the oscillations. This rule distinguishes entrainment from other phenomena, such as *resonance* for example, where the oscillations stop as soon as one oscillating body (e.g. tuning fork) detaches from the other (e.g. resonance box). This in essence means that, an observation of synchronised behaviour or even a synchronous variation between two variables does not necessarily indicate entrainment.
- b) **There must be a link to allow the oscillations to interact.** A link or coupling must exist between the oscillators, which is weak enough so as not to cause the oscillators to lose their ability to oscillate autonomously (see point (a) above), but it should be strong enough to link the interaction between the oscillators.

Synchronisation between two oscillating bodies or rhythmic processes does not happen instantaneously or automatically. There are also cases where oscillators may never synchronise at all. Different factors may dictate if oscillating bodies will entrain and their entrainment possibilities (Clayton, Sager and Will, 2005). These factors are listed below:

1. Periodicities¹ of autonomous oscillators need to be relatively close to each other, or to be related by whole number ratios².
2. Entrainment does not occur instantly. Sufficient time, depending on the different oscillators and their coupling, needs to be allowed for entrainment to occur. When, for example, Huygens first defined entrainment, he noted that pendulums would start moving in synchrony after thirty minutes (Ancona and Chong, 1999). However, biological entrainment is said to occur in much shorter periods of time, with studies using finger tapping methodologies observing participants tapping in synchrony to an external rhythm after three taps (Repp, 2005).
3. Two distinct aspects of entrainment can be distinguished but they don't necessarily need to co-occur. These are:
 - a. Frequency or tempo entrainment where frequencies or tempi adjust in a similar relationship.
 - b. Phase entrainment where two processes are phase-locked, with focal points happening at the same moment (e.g. such as a foot striking the floor when dancing).

¹ The frequency accent phases are occurring in a period of time.

² For example, typically oscillators with periodicities in ratios such as 2:1, 3:1, or 3:2 can readily entrain, as generally can oscillators with periodicities in ratios such as 2:2.01. However, ratios such as $e:\pi$, would generally not lead to entrainment. The exact numerical extent, in particular cases, to which periodicity ratios need to be close to each other depends on factors such coupling strength.

4. Entrainment may be weak between oscillators. In some cases, a rhythmic process may adjust towards the frequency or period of another rhythmic process without ever reaching absolute entrainment.
5. Exact phase is not the only instance where entrainment can occur; it can also occur in anti-phase. Human gait is an example of anti-phase since one foot goes up as the other comes down (Clayton, Sager and Will, 2005). The number of possible phase related states increase with the number of oscillators.

An important point that comes out of the concept of entrainment is that it must not be assumed that entrainment necessarily involves synchronisation of phase. In real life systems, this is not always the case since two periodic processes may lock frequency, but remain out of phase.

Bluedorn in (Bluedorn, 2002) (p148) summarises entrainment as: “[a] process in which the rhythms displayed by two or more phenomena become synchronised, with one of the rhythms often being more powerful or dominant and capturing the rhythm of the other. This does not mean, however, that the rhythmic patterns will coincide or overlap exactly; instead, it means the patterns will maintain a consistent relationship with each other”.

2.2.3 Rhythm and time perception - Neural entrainment

Although Christiaan Huygens (see above) defined entrainment in mechanical rather than biological systems, and much of the succeeding work on entrainment (both theoretical and applied) has been carried out within the fields of mathematics and physics, the main emphasis in this thesis is on the entrainment of physiological rhythms in humans. More specifically, the focus of the present thesis is rhythmic cueing using the *sense of touch*. However, most research on rhythmic cueing has been carried out using not touch, but the *sense of hearing*. Consequently, in the sections below, this thesis will use the literature of the more established rhythmic *auditory* entrainment.

The human auditory system has the ability to rapidly and accurately detect temporal patterns in audio signals and construct stable temporal templates (Thaut and Kenyon, 2003). This allows humans to synchronise movements with external rhythms without apparent effort (Repp, 2005).

Michael H. Thaut, a well-known music therapy researcher, and Professor of Music and Neuroscience, first identified the effect of rhythm and auditory entrainment on healthy participants (i.e. those *not* suffering from any neurological conditions causing gait related deficits). Participants in these early studies were found to synchronise their steps to the music, entraining their movement to the beats of the rhythm, helping them walk better to music than they did without in terms of stride rhythmicity and muscle activity by producing more focused motor unit recruitment patterns (Thaut *et al.*, 1992).

The results from that study led to the realisation of the potential music, and more specifically rhythm, has on assisting with gait rehabilitation of people suffering from gait deficiencies as a result of a neurological condition or brain trauma. Follow-up studies (Thaut *et al.*, 1993; Thaut, McIntosh and Rice, 1997) with hemiparetic patients (hemiparesis is discussed further as a neurological condition in section 2.5.1) confirmed rhythmic entrainment processes in clinical populations. Studies also extended entrainment to hemiparetic arm rehabilitation (Whitall *et al.*, 2000; Thaut *et al.*, 2002), however arm rehabilitation falls outside the scope of this thesis.

As discussed in section 2.2.2 above, two conditions must be satisfied for entrainment to take place; the two rhythmic processes or oscillators must be autonomous, being able to oscillate on their own, and a link must exist to allow the two oscillators interact. In the case of neural entrainment, the rhythmic processes are the external rhythm and the walking movement (how the walking movement can be described as an oscillator is further explained in section 2.3.1). In such cases, the link between the processes is the brain and the central nervous system including the sensory channel through which the rhythm is

perceived and the motor areas and neurons activating and coordinating muscle movement.

Neurological entrainment is fundamentally related to the temporal pattern of the stimulus (in relation to its tempo). After listening to just two or three beats of a steady, isochronous rhythm, most humans can tap to the same rhythm in almost perfect synchrony. Studies like (Thaut, Miller and Schauer, 1998) and (Large, Fink and Kelso, 2002) indicate that motor movement during index finger tapping can entrain to the period of a metronome beat, and stay locked even when subtle tempo changes are brought into the metronome (Thaut *et al.*, 1999).

This ability to detect temporal patterns and synchronise motor movements to their rhythmicity provides a fundamental contrast with models of interaction such as simple stimulus response or pattern recognition: see Figure 3 for examples.

Stimulus response and pattern recognition are often used for purposes of attracting attention and have no direct relationship to the entrainment process discussed in this thesis. As shown in Figure 3, stimuli can be simple cues, or simple patterns conveying a message - e.g. (Shakeri, Ng and Brewster, 2016) where different tactile cue patterns convey different messages to the user.

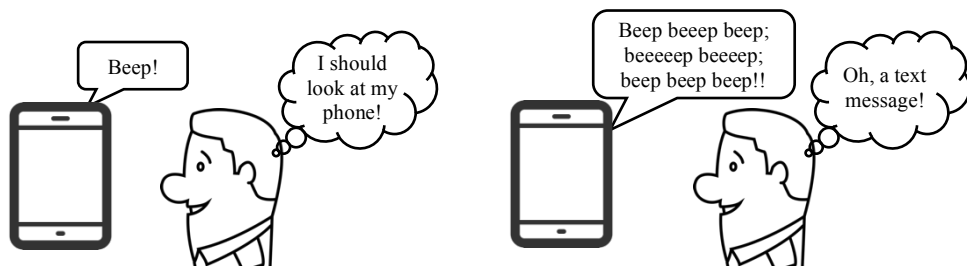


Figure 3 Example of a stimulus-response interaction involving pattern recognition. Left: mobile beeps once, notifying the user of an event. Right: mobile phone beeps in a pattern once. The user understands this stimulus pattern means there is a new text message on their phone.

In the case of neural entrainment, exact synchronisation, or entrainment of movement, to external rhythm is both due to local spinal circuits, called central

pattern generators (CPGs) and a rich connection between the auditory and motor mechanisms in the brain. Firstly, CPGs help to enable movement by connecting directly incoming sensory information to the appropriate motor neurons. This makes CPGs capable of initiating and coordinating movement with no input from the brain. This is particularly interesting when considering rhythm-based rehabilitation for patients suffering from brain damage; such as after a stroke.

The direct connection between sensory and motor mechanisms allows for a much faster and sometimes subconscious motor response to rhythm, entraining to an exact temporal pattern. Studies investigating people tapping their finger to an auditory rhythm found that participants could very easily unconsciously adjust their tempo to match perturbations in the target auditory tempo (Thaut, Miller and Schauer, 1998; Repp, 2000). Rhythm entrainment working below consciousness has important implications for people with disrupted mental ability during movement coordination. These implications are further discussed in the findings section of the technology probe formative study presented in Chapter 4 (page 60).

The ability to entrain with little or no conscious effort may be connected with the way that the sensory system is organised, as follows.

The auditory system has richly distributed fibre connections to motor centres from the spinal cord upward on brain stem, subcortical, and cortical levels (Thaut, McIntosh and Hoemberg, 2015). Therefore, the mechanism of rhythmic entrainment may be strongly based on direct, dynamic, sensorimotor coupling, helping to explain why it can happen without any major cognitive learning effort (Thaut, 2007). Interestingly, this leaves open related questions concerning entrainment to haptic cues, a topic that will be returned to in Chapter 5.

2.2.4 Identifying entrainment in gait

As discussed in section 2.2.3 above, given the right conditions, rhythmic bodily movements can readily be entrained to external rhythms. Sources of evidence at the neural level for this kind of entrainment can be found in studies from Electroencephalogram (EEG) and electromyography (EMG). For example, EEG can be used to capture electrochemical pulses in the neural networks between the sensory and motor areas of the brain showing rhythmic synchrony of such pulses with the external rhythm (Gerloff *et al.*, 1998). Similarly, EMG can be used to detect the electrochemical signals reaching certain muscles involved in the rhythmic movement (Thaut *et al.*, 1993). These are all candidate techniques for identifying entrainment, albeit using complex instrumentation, however, simpler forms of evidence exist, more practical and applicable for most gait studies.

Researchers in various disciplines routinely use relatively simple methods for identifying the effects of entrainment on motor movement. By identifying the effects of rhythm on a person's movement, researchers can infer the presence of entrainment between the movement and the external rhythm. For example, in the case of finger tapping experiments, these effects include:

- reductions in variability (Repp, 2006a),
- synchronisation of movements to the beat of an external rhythm (Repp, 2005).

In gait experiments, using video captures (Prassas *et al.*, 1997) and pressure sensors (Roerdink *et al.*, 2011; Wright *et al.*, 2013) entrainment effects include:

- visual observation of synchronisation of footfalls to an external beat

- improved symmetry³ in spatiotemporal data (Wright *et al.*, 2013).

In accordance with these approaches to identifying entrainment, and in accordance with the principles laid out by Clayton (section 2.2.2), in this thesis, evidence such as visual observation of synchronisation of footfalls to an external beat, and improvements in gait symmetry (in particular temporal symmetry) will be used as evidence of entrainment.

2.3 Human gait

As Thaut and Rice state (Thaut and Rice, 2016)⁴: “*Gait is beautifully simple and complex at the same time*”. Gait, and the process of walking, is a motor skill humans learn to develop from a young age. Most babies take their first steps sometime between 9 and 12 months and are walking by the time they are 14 or 15 months old⁵. Learning to walk confidently and efficiently usually takes months of practising and the achievement of numerous subtasks, such as balancing on two feet while maintaining upright posture. The practice and repetition of these skills helps to eventually refine them, making them more or less automatic. Walking is so much involved in everyday life, that not much thought is given to it until it goes wrong.

³ The implications of symmetric gait to a person’s overall health are discussed in section 2.5 on page 28.

⁴ (Thaut and Rice, 2016) publication refers to the work by Corene H. Thaut and is not to be confused with Michael H. Thaut whose work is reference throughout this thesis.

⁵ Source: www.babycenter.com/0_baby-milestone-walking_6507.bc [Accessed: 31/07/2018]

2.3.1 Gait as an oscillator

For reasons of clarity when assessing gait, it is useful to break walking down to various constituent elements, and introduce some terminology. In essence, for each step, the foot lifts off the ground, swings forward, hits the ground and stands until ready to lift off again, forming one step cycle (see Figure 4).

Multiple step cycles happen for each alternating leg. Therefore, each leg acts as an oscillator performing a fundamentally cyclic process on every step.

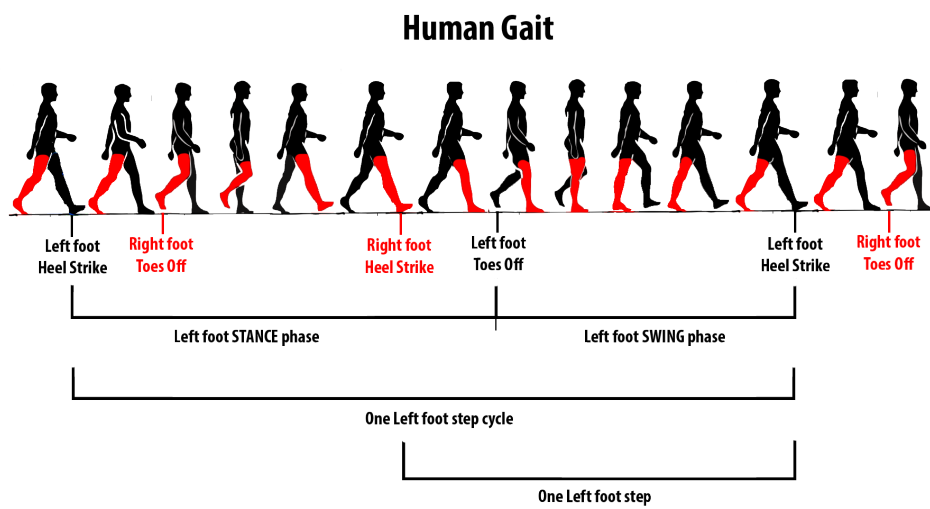


Figure 4 Phases in human gait. The swing phase, as the name suggests, is defined from the moment the toes of the foot initiating the step lift off the ground and the leg begins to swing forward. This phase completes when the heel of that foot strikes the ground, starting the stance phase. Between each two successive step cycles of alternating legs, there is also what is known as the “double support” phase, where both legs touch the ground (time between heel strike and toes off of the next leg). This is an integral part of walking, but double stance time does not affect how gait symmetries are calculated in this thesis (see section 2.3.2, page 24).

Consequently, since gait patterns are intrinsically cyclical, they can be entrained to external rhythms just like any other oscillator described in the field of physics and mathematics. Given that rhythm and gait rehabilitation are focal points of this thesis, the capacity of gait to entrain with external rhythms is of vital importance.

Considering gait kinematics, each step cycle, consists primarily of two phases; the swing phase, where the leg swings forward, and the stance phase, where the foot is standing on the ground, supporting the body's weight. These phases are two of the most important gait characteristics used for assessing gait (more to follow in section 2.3.2 below). Figure 4 provides an illustration containing the phases of human gait.

2.3.2 Assessing gait

Assessing gait and classifying stroke survivors based on 'ambulation capability' is an important aspect of rehabilitation treatment. Historically, walk velocity is used to assess patient's gait due to the ease by which it can be recorded and applied in the clinical setting. For this metric, all a physiotherapist needs to do is time a patient while walking a known distance. This method of assessing gait only requires a stopwatch and no specialised or extensive laboratory setup.

While walk velocity can be reflective of gait performance, it does not have sufficient "*explicative capacity*" needed in discriminating among post-stroke ambulators (Perry *et al.*, 1995). Therefore, as neuro-physiotherapists and rehabilitation experts argue (Olney, Griffin and McBride, 1994; Lord, Halligan and Wade, 1998), using walk velocity alone neither assists in understanding the nature of gait deficits, nor supports direct treatment for stroke survivors. This makes walk velocity alone limited in value in documenting and assessing recovery from stroke.

Walk velocity as measured in the clinic, is also commonly used to predict the walking ability of a person in the community. Walk velocity makes up an important assessment tool physiotherapists use, not only for assessing patients and their progress, but for communicating with other health professionals their patients' walking abilities. Dr Jacquelin Perry, an American physician, defined a widely accepted velocity classification scale for stroke survivors (Perry *et al.*, 1995):

- up to 0.4 m/s for “household capability”;
- 0.4 to 0.8 m/s for “limited community capability”;
- more than 0.8 m/s for “full community capability”.

However, in a study comparing clinic and community based walk velocity measurements, Denise Taylor, a physiotherapy lecturer, and her colleagues, (Taylor *et al.*, 2006) found that classification from measurements taken in the clinic alone does not translate to a community setting unless the walk velocity is greater than 0.8m/s. This was an interesting finding, suggesting that walk velocity based classification systems are of limited scope and do not translate accurately from the clinic to the community environment.

Spatial and temporal symmetry, on the other hand, may be an additional and valuable measure (Patterson *et al.*, 2008) that can be used when trying to characterise ambulation capabilities. This may be of particular relevance in further discrimination of post-stroke ambulators; more specifically those with gait speeds less than 0.6m/s. In particular, gait symmetry has the potential to provide rich insights linking observations to gait deficiencies, balance control, risk of musculoskeletal injury to the non-paretic lower limb and loss of bone mass density in the paretic lower limb (Patterson *et al.*, 2008). Symmetry information, *combined with* walk velocity information, can be used to paint a more complete picture of an individual’s gait capabilities, helping the physiotherapist assess patients better and decide on the best rehabilitation action.

However, unlike walk velocity, measuring and analysing spatial and temporal symmetry typically requires expensive laboratory setups.

2.3.3 Current gait assessment techniques

Acquiring accurate and reliable knowledge of gait characteristics can enable quantification of progress during rehabilitation and simplifies communication of the patient’s status between health professionals, thus helping to find the

best treatment. Traditionally, the tests and measurements used for analysing gait parameters in clinical conditions are semi-subjective, carried out by specialists who observe the quality of a patient's gait while walking or while performing certain walk related actions. One example of such a test is the '*timed up and go*' (TUG) test. During the TUG test, the health professional times the time it takes for the patient to rise from a chair, walk three meters, turn around, walk back to the chair, and sit down. Tests such as TUG are then usually followed by a survey in which the patient is asked to give a subjective evaluation of the quality of their gait. The answers can then be scored giving a descriptive figure for the health professional to use for their assessment. One example of such a survey is the Rivermead mobility index (see Appendix 2, page 187). The disadvantage of these methods is that they rely on subjective measurements and may lack accuracy and precision. As discussed in section 2.3.2 above, physiotherapists may also time patients, and calculate their walk velocity as a measure for gait capabilities assessment. Even though there are arguments against its accuracy and how well it translates to gait capabilities outside the lab environment, physiotherapists still use this method of walk velocity measurement because of its ease of application.

Advances in technology allow more objective evaluation of different gait parameters. More objective evaluations have the potential to provide specialists with more reliable information on patients' gait characteristics and reduce the ambiguity caused by subjective techniques. An exhaustive review on gait monitoring technologies would be outside the scope of this thesis. However, it is useful to briefly consider some representative approaches.

Gait monitoring technologies can be divided into two main categories: *wearable*, and *non-wearable*. Non-wearable technologies typically require the use of controlled research facilities. The relevant sensors are generally either *optical*, where image processing is used to track motion (an example can be

seen on Figure 5); or based on *floor sensors* where motion is captured by monitoring pressure changes on the floor (as seen on Figure 6).

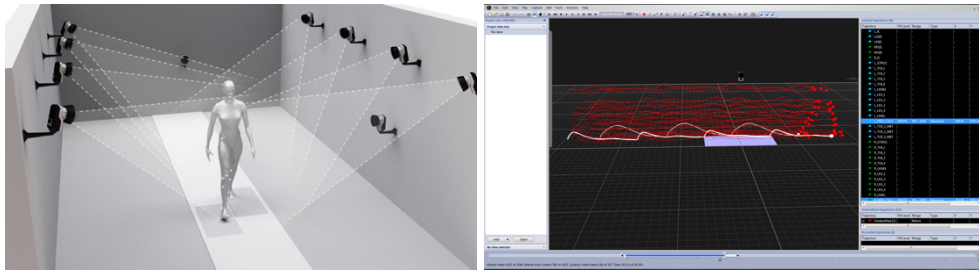


Figure 5 Example of an optical motion tracking technology. Left: default setup of a Qualisys motion capture system. Right: an example of data recorded by the system.

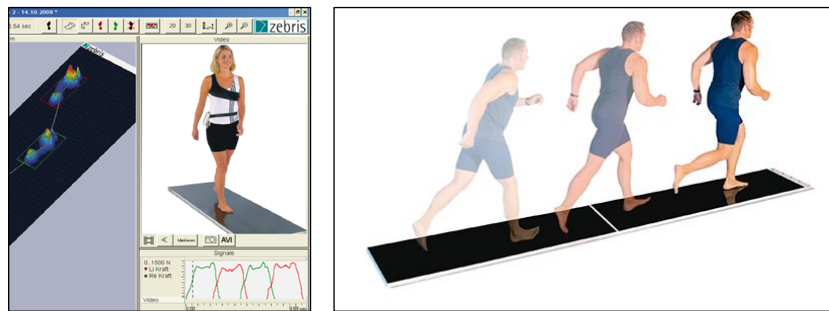


Figure 6 An example of a non-wearable technology for gait monitoring using floor sensors. The floor sensors of this particular “zebris FDM Stance and Gait Analysis System” are within a mat capturing changes in pressure force while a person walks over it. Images taken from manufacturer’s official website.

Although non-wearable systems can provide highly accurate results and a detailed and objective evaluation of different gait parameters, there are disadvantages to their use. Systems that use optical motion tracking or floor sensors are typically expensive and require their own dedicated lab space. The “capture volume” of such technologies is restricted to the size of the room, or by size restrictions of the installation (e.g. the length of the floor sensor array, or camera viewing angles).

In contrast, wearable technologies, where sensors are placed directly on the patient’s body, allow for data to be captured and analysed outside the laboratory. This allows for greater flexibility on their use and gives the

additional advantage of collecting information about gait during the person's everyday activities. Detailed information can then be collected on a person's gait during normal community-based activities, using data from much longer sessions. Wearable technologies do however have their own distinctive limitations; ranging from restrictive battery life to inaccuracies occurred by hardware limitations and improper operation during self-managed use.

Wearable sensor placement is also often restricted to the wrist: for example, by watches and bracelets (e.g. fitbit and Apple Watch – see Figure 7). There is some notable exception among specialised systems such as 'GaitSmart' – see Figure 8. Wrist placement can complicate gait monitoring, since often patients suffering from hemiparesis (as this is the main focus of this research) have disrupted upper limb movement which may introduce further inaccuracies and limitations.



Figure 7 Commercially available activity trackers with gait monitor capabilities. Left: fitbit Surge. Right: Apple Watch. Images taken from manufacturer's official website.



Figure 8 GaitSmart gait tracking and analysis system. Images taken from manufacturer's official website.

2.4 Calculating gait symmetries

As discussed in the section above, there are diverse technologies for the collection of gait characteristics. This section considers the analysis of the relevant data and how it can be used to characterise a person's gait, particularly their spatiotemporal (i.e. both spatial and temporal) symmetry. In order to understand how to use spatiotemporal gait *parameters* to calculate gait symmetry, a good starting point is to consider the various *equations* for gait symmetry.

Symmetry equations

Broadly two types of equation are generally used for assessing gait symmetry: the first considers *ratios*, and the second uses *indices* or *difference* calculations.

The symmetry equations dealing with ratio can be further divided in two variations: one considering log transformation of the ratio of right and left swing times (Plotnik, Giladi and Hausdorff, 2007), and one where the symmetry angle (formed by the x-axis and the vector created by plotting the right and left values of a discrete gait parameter) is used (Zifchock *et al.*, 2008). The resulting equations are stated below. Opposite limbs in these equations are described as “paretic” and “non-paretic” where paretic is the term used for describing the leg affected by the gait related neurological condition (further information on section 2.5.1, page 27).

Note that all of the following equations are presented in an abstract form, where a single equation, for example

$$SR = V_{paretic}/V_{non-paretic}$$

summarises a family of equations. For example, the role of V in the above equation can variously be taken by a variety of spatial or temporal parameters, including: swing time, stance time, step time or stride length. The key requirement is that generally, swing time must be compared with swing time,

stance time with stance time, and so on – parameters must not be mixed (though one exception to this rule is discussed below).

Symmetry ratio (SR):

$$SR = V_{paretic}/V_{non-paretic} \quad (1)$$

Symmetry index (SI):

$$SI = [(V_{paretic} - V_{non-paretic}) / (0.5 \times (V_{paretic} + V_{non-paretic}))] \times 100\% \quad (2)$$

Gait asymmetry (GA):

$$GA = |100 \times [\ln(V_{paretic}/V_{non-paretic})]| \quad (3)$$

Symmetry angle (SA):

$$SA = [(45^\circ - \arctan(V_{paretic}/V_{non-paretic}) \times 100\%)] / 90 \quad (4)$$

(Patterson *et al.*, 2010) compared these four equations for discriminative ability using gait related data from 161 stroke survivors and eighty-one healthy participants. The conclusion from this comparison was that none of these equations demonstrated a clear advantage in this respect. Yet, as also noted by Patterson *et al.*, the symmetry ratio equation (1) affords the advantage of ease of interpretation, as it boils down to a simple ratio combining values from the paretic and non-paretic limb to give a numerical measure of gait; where a value of ‘one’ indicates perfect symmetry.

For this reason, the ratio equation (1) will be used when describing the results of the studies presented in Chapter 7 (page 121).

Symmetry calculation parameters

Other important metrics for characterising a person's gait can be calculated by combining spatial and temporal parameters. Combining step length and step time, for example, gives walk velocity.

Symmetry calculations based on different spatial and temporal gait parameters can give distinctive information about an individual's control of walking. For example, asymmetry in stance versus swing time may provide insight into different challenges in the control of each gait phase. Symmetry calculations between paretic and non-paretic limb values can also form a single figure characterising a person's gait. One such calculation is the *overall temporal asymmetry* ratio, discussed below.

2.4.1 Overall Temporal Asymmetry (OTA) ratio

Firstly, the swing-stance ratio is calculated for each leg (5). This is a ratio (simple division) between the swing (SW) and stance (ST) time for each leg in turn.

$$\text{Swing/stance ratio} = \frac{SW}{ST} \quad (5)$$

The OTA ratio is then simply the ratio of the swing-stance ratio of the paretic compared with the non-paretic leg – (6).

$$\text{Overall temporal symmetry} = \frac{SW_p}{ST_p} / \frac{SW_{np}}{ST_{np}} \quad (6)$$

For a healthy individual, the value for OTA should be between 0.9 and 1.1 – a range described as healthy or normative (Patterson *et al.*, 2008). In the case of neurological conditions, higher swing-stance ratios are commonly seen. For example, in the case of hemiparesis (further described in the next section), one side of the body is affected unilaterally, typically causing the affected leg to swing more slowly. Due to weakness and sensitivity loss, a stroke survivor

often loses trust in the affected leg, doubting it can support them. This further causes them to swing the non-affected (non-paretic) leg faster in order to minimise the time spend standing on the affected leg. Consequently, the swing time of the good (non-paretic) leg decreases (i.e. swings faster), causing the stance time of the paretic leg's also to decrease.

These combined changes in stance and swing times of both legs raise the OTA value. Hence, while 0.9 to 1.1 describes *normal* asymmetry, values between 1.1 to 1.5 describe *mild* and over 1.5 *severe* asymmetry (Patterson *et al.*, 2008). Entraining to an external rhythm has been shown to reduce gait asymmetry and result in a more symmetric and less variable gait pattern (Thaut, 2007) (this point will be revisited in section 2.6, page 29).

2.4.2 Gait variability assessment

In addition to changes in *symmetry*, neurological conditions often make spatial and temporal gait characteristics more *variable*.

The Coefficient of Variation (CV) is used in this thesis to calculate gait variability (see equation (7)). This measure is the ratio of standard deviation (σ) and mean (\bar{x}) - intuitively, smaller values mean reduced variability.

$$CV = (\sigma/\bar{x}) \times 100 \quad (7)$$

The CV is chosen for this research, instead of the standard deviation alone, because it is a more useful way of characterising variability in the presence of widely varying means. Thus, direct comparison of values can be made without worrying about the magnitude of the mean.

2.5 Stroke and gait asymmetries

Stroke has existed as a medical term since at least the late 19th century, with one of the earliest documented entries being in an 1803 book (Foxe, 1803) (p.195), where the author describes how a person was “stricken on the right

side with such a palsy or *stroke of God's hand* [...]” before proceeding to describe the condition we now know as stroke.

In medical terms, stroke refers to a cerebrovascular accident, caused by either an obstruction or a hemorrhage (Cohen, 1999). Both conditions result in parts of the brain dying with subsequent motor control loss that may affect gait. Even though the detailed medical background is strictly speaking outside the scope of this thesis, it may be useful to explain what is meant by “*obstruction*” and “*hemorrhage*”.

An obstruction is caused when a blood vessel carrying blood to the brain is blocked, either by build-up of plaque or by the formation of a clot that arrived through the circulation from another part of the body. This is often referred to as ischemic stroke (Cohen, 1999).

Hemorrhage (or hemorrhagic stroke) (Cohen, 1999) occurs when a blood vessel near the brain bursts. Loss of blood supply causes an infarction in the area fed by the vessel and the surrounding cells begin to die. Causes of an ischemic or a hemorrhagic stroke include: stress, a blood clot from another part of the brain reaching the brain through the blood circulation system or a head trauma as a result of an injury.

2.5.1 Hemiparesis

In most cases of stroke and brain injury, the blood supply to specific areas of the brain responsible for motor coordination and control is compromised. This may lead to weakness of the contralateral limbs, in a condition known as *hemiparesis* (Cohen, 1999). With hemiparesis, stroke survivors can still move the affected side of their body, but with reduced motor control and muscular strength.

Motor control deficiencies leads to spatial and temporal asymmetries between steps in a condition known as “*hemiparetic gait*”. The asymmetries can cause sufferers of hemiparetic gait to overuse their non-affected (non-paretic) leg,

exposing it to higher vertical forces (Kim and Eng, 2003), while underusing the paretic (affected) leg. This underuse can subsequently lead to loss of muscle tone and reduction of bone mineral density (Min *et al.*, 2016). These effects in turn increase the risk of knee and joint problems, leading to an increased risk of hip and bone fractures, and raise the risk of falls (Wen *et al.*, 2010). Regular rehabilitation exercises can significantly improve a person's recovery both in the early days after a stroke and long after they return home (Galvin, Cusack and Stokes, 2009).

This recovery is facilitated by the brain's ability to form new connections, bridging damaged parts and restoring lost functionality in a process known as *brain plasticity*.

2.5.2 Brain plasticity

Brain neuroplasticity (or just plasticity) is the term used to describe the brain's capability to reorganise the motor map in the brain to bypass damaged areas and form new connections, assisting the recovery of lost function (Cohen, 1999). Rehabilitation after brain trauma (injury or stroke) focuses on relearning an essential ability that has been lost as a result of the trauma. Through appropriate training – the driving force of brain plasticity in the chronic condition (Rossini *et al.*, 1998) – restoration of function is possible, mediated by actual changes in neural networks of the brain “circuitry”. Specifically, the motor cortex, the region responsible for the planning, control, and execution of voluntary movements, can rapidly reorganise the brain's cortical map in response to retraining of skilled motor tasks (Belda-Lois *et al.*, 2011).

2.6 Entrainment and gait rehabilitation

Before exploring rehabilitation and its effects in conjunction with *brain plasticity*, a brief remark on the use of the term “rehabilitation” and its meaning in the context of this thesis is needed.

Considering the strictest semantic sense, the use of the word “rehabilitation” only applies to illnesses and disorders that allow for actual and full restoration of function (Cohen, 1999). However, when applied to neurological conditions and diseases that may cause neuron degeneration and neuron death such as Parkinson’s, Ataxia, Huntington’s disease, or even to hemiparetic stroke, the strict definition of rehabilitation no longer applies because it is not expected that the patient will ever fully recover. “Habilitation” or “adaptation” may be considered more suitable. However, in common use, the term rehabilitation is used more flexibly than what the technically correct semantic meaning implies. Therefore, in this thesis, the term “rehabilitation” is used in such a broader sense.

As explained in section 2.2 of this chapter (page 8), external rhythms can entrain with motor movements to facilitate training (i.e. rehabilitation) of movement that is intrinsically and biologically rhythmical; and gait is arguably the most important of this type of movement in humans (Thaut, 2007) (p.138). As already discussed in the sections above (section 2.5.2, page 29), the brain has considerable plasticity that can be shaped and controlled by experience, learning and performing repetitive activities. Repetitions also help to promote brain plasticity and restitution of motor function through actual changes in neural connections in the brain (Thaut, 2007).

As one special case of this, external rhythms can be used for gait rehabilitation for people suffering from conditions causing gait deficiencies (such as hemiparesis – section 2.5.1, page 27). Studies have shown that walking to an auditory rhythm can help to regulate gait and reduce gait asymmetries (e.g. (Roerdink *et al.*, 2007; Wright *et al.*, 2013)). In section 2.6.3 the relationship between neuroplasticity and entrainment-based rehabilitation will be explored in more depth.

2.6.1 Rhythmic auditory stimulation (RAS)

Rhythmic auditory stimulation (RAS) is a neurological technique used for facilitating rehabilitation, development and maintenance of movements that are fundamentally biologically rhythmical. As discussed above and in section 2.3.1 (page 18), gait is intrinsically rhythmical, in that during the action of walk there is a set of phases that occur sequentially and repeat for every step. RAS applies the physiological effects of entrainment between the auditory rhythm and the motor system (section 2.2.3) to improve the control of movement in rehabilitation of functional stable and adaptive gait patterns of people with gait deficits (Thaut, 2007). Today, RAS is an established rehabilitation technique for improving limb coordination (both upper and lower) and helping to decrease gait asymmetry and variability during walk (Thaut and Rice, 2016).

2.6.2 Neurological principles of RAS

In total, four neurological principles help to define RAS as a neurological technique for facilitating gait rehabilitation. These four principles are:

- rhythmic entrainment,
- priming movement,
- movement period cueing, and
- stepwise limit cycle entrainment (Thaut and Rice, 2016).

Rhythmic entrainment

Rhythmic entrainment has been explored in detail in section 2.2, page 8.

Priming movement

Priming of movement effectively means making the muscles ready to move. With the neurological principle of priming, external cues stimulate recruitment of motor neurons in the nervous system. Studies using brain imaging techniques during rhythmic motor synchronisation identified limited activation

of the prefrontal cortex of the brain – area associated with the planning of complex cognitive behaviour (Stephan *et al.*, 2002). This limited activation of the prefrontal cortex supports the concepts of a direct sensorimotor coupling during entrainment of movement to a rhythm without direct input from the brain (Thaut, 2007) (p. 142).

The priming of muscles following an external rhythmic stimulus has shown decreased variability in muscle activity as measured by electromyography (EMG), indicating more efficient recruitment of the motor units necessary in repetitive skilled movement (such as walking) (Thaut, Schleiffers and Davis, 1991). Temporal parameters of the step cycle (see section 2.3.1, page 18) and electromyography measures (EMG) – measurements of the electrical activity produced by skeletal muscles – both indicated improvements during normal gait with cueing (Thaut *et al.*, 1992). These results indicate more focused and consisted motor activity due to priming effects, with similar results extending to hemiparetic gait and stroke patients (Thaut *et al.*, 1993).

Movement period cueing

Rhythmic synchronisation of the motor system to an external stimulus is driven primarily by frequency entrainment rather than strict event synchronisation between the rhythmic events (e.g. auditory beats) and the motor response (Thaut, McIntosh and Rice, 1997). Therefore, entrainment is relying on an *anticipation model*, where the next rhythmic event is anticipated instead of responding to it retrospectively. This anticipation instead of an ad hoc response is a major difference between entrainment and stimulus-response interaction discussed in section 2.2.3 above. Hence, the time stability of the motor movement is enhanced throughout its duration and trajectory, and not just at the endpoint of the movement that coincide with the period of the external stimulus's rhythm (Thaut *et al.*, 2002).

Stepwise limit cycle entrainment

The limit cycle is defined as the step cadence (i.e. number of steps per minute) at which a person's gait optimally functions (Thaut and Rice, 2016). The limit cycle can be changed due to a neurological disease, brain injury or trauma causing deficient gait patterns. With the RAS technique, neurological disease patients or stroke survivors start by entraining their steps to an external rhythm matching their affected limit cycle, before gradually progressing in a stepwise fashion, modulating the rhythm and their cadence to approximate premorbid movement frequencies (Thaut and Rice, 2016).

In summary, the four principles described above help to make rhythm a beneficial tool for gait rehabilitation of people suffering from gait deficits as a result of a neurological condition. The *entrainment* principle allows the close synchronisation of movement to the rhythm a stimulus is delivered at; the *priming* of the motor system and the *anticipation model* mean all relevant muscles are ready to act in a precisely planned and choreographed manner, while the *stepwise limit cycle* defines the rhythm's tempo for optimum entrainment.

2.6.3 Other gait rehabilitation techniques

Other rehabilitation techniques exist for treating people with neurological conditions. Bobath therapy (Bobath, 1990), or 'neuro-developmental treatment (NDT)', as it is known in the US, is one of the most commonly practiced gait rehabilitation techniques worldwide (Patterson, 2010). This technique usually involves a multidisciplinary team of specialists including physiotherapists, occupational therapists and speech and language therapists. During Bobath therapy sessions, patients learn how to perform and control simple postures and movements, before gradually progressing to more difficult exercises (Cohen, 1999).

Comparing RAS to the gait rehabilitation aspects of this more traditional rehabilitation technique, walking following a steady auditory rhythm showed significant gains in stride length (distance between subsequent heel strikes) and cadence (steps per minute) after a shorter period of therapy (Thaut *et al.*, 2007). However, (Thaut *et al.*, 2007) reported no clear research evidence for the effectiveness of one approach over another.

2.6.4 RAS assisted rehabilitation

Early studies by (Prassas *et al.*, 1997) using RAS have shown immediate spatial benefits, with stride lengths becoming more symmetrical. In addition, (Prassas *et al.*, 1997) found the hip joint range of motion to increase and the centre of mass displacement decrease during walk with RAS, making the overall forward movement smoother.

More recent studies involving participants walking on a treadmill, found that stroke survivors could easily synchronise their steps to a rhythmic audio metronome, showing improvements in temporal symmetries, such as: step time asymmetry between the paretic and the non-paretic leg (Roerdink *et al.*, 2007), and the reduction of variability in the paretic step times (Wright *et al.*, 2013).

These results indicate that RAS, and by extension, walking to a rhythm, has a strong clinical significance since step asymmetry is the leading cause of most of the problems associated with neurological conditions such as hemiparetic gait (Thaut *et al.*, 2007). Specifically, improvements in symmetry and variability may suggest a more functional recovery of gait mechanics as they are kinematically linked with healthy gait (Thaut *et al.*, 2007).

2.7 Rhythmic haptic cueing (RHC)

Existing discussions of RAS in the literature are conducted exclusively in the context of *audio* entrainment (as suggested by the name - Rhythmic Audio

Stimulation). However, given the focus of this thesis on haptic entrainment, the next section considers the literature relevant to rhythmic *haptic* cueing.

2.7.1 Definition of haptics

Haptics refers to the sense and manipulation through touch, and can refer to any form of non-verbal communication involving touch (Srinivasan, 1995). The word haptics derives from the ancient Greek word “*απτικό*” (*háptikō*) and translates directly to “*by touch*”. This term, in its original form, entered English in the late 19th century as a medical synonym for “tactile” and has been used widely since the early part of the twentieth century by psychologists for studies on the active and passive touch of real objects by humans (e.g. (Lederman S. J., 2009)).

Advances in technology during the later parts of the twentieth century encouraged researchers from other disciplines to consider novel touch-based ways of interacting with machines. However, instead of creating a new name, researchers at the time decided to redefine the pre-existing term for ‘haptics’ by broadening its scope to also include machine touch and human machine touch interactions (Srinivasan, 1995). This broadening of the definitional scope, meant an increase in ambiguity, with many different definitions being used throughout the literature to describe haptic interaction.

The need for a universally accepted definition was apparent, with several researchers attempting to define terminologies for haptics (e.g. (Srinivasan and Basdogan, 1997; Oakley *et al.*, 2000)). To rectify this emerging problem, Erp *et al.* (Van Erp *et al.*, 2010) published their own definition which soon became the widely accepted ISO definition for haptics (International Organization for Standardization, 2011).

This new definition of *haptics* made a clear distinction between touch (tactile) sensation and kinesthesia (relating to movement and position sensation of muscles, tendons and bones) as a mode of interaction with the immediate

environment. In other words, touch and kinesthesia can be defined as subgroups of the broader term referred as haptics.

These two subgroups are then further divided into more subcategories, each with their own definitions. Figure 9 below summarises the term haptics and shows the relationship between the components that make up the field of haptics. The focus of this thesis is primarily the tactile branch of haptics, with the rhythmic haptic cue (see section below) being delivered through small vibrators, creating *mechanical stimulation* on the skin.

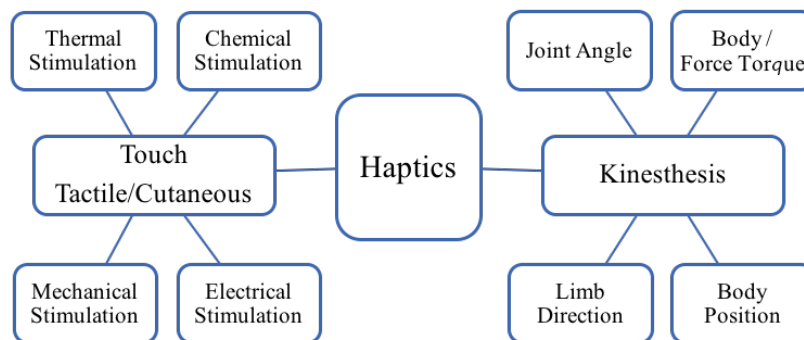


Figure 9 The components of haptics. "Touch" includes such diverse stimuli as mechanical, thermal, chemical and electrical stimulation to the skin. The "kinaesthetic" sense can be matched by kinaesthetic activity by which a user exerts force or torque on an object external to the active body part (Van Erp et al., 2010).

2.7.2 Motivation for RHC

As mentioned above, existing discussions of RAS in the literature are conducted exclusively in the context of *audio* entrainment (as suggested by the name - Rhythmic Audio Stimulation). However, there are circumstances where audio cues may be undesirable or unsuitable, for example in cases where there is some hearing loss, or when wishing to maintain full environmental awareness of traffic and other people, or when preferring to maintain full social engagement. In addition, the way audio cues are presented to patients during rehabilitation in the clinic has its own set of limitations. In order to maintain communication between patients and physiotherapists, audio cues are usually

played out through speakers. As discussed in section 2.6.2 above, for optimum entrainment results, the tempo must match the patients walking pace.

Therefore, only one patient can receive the audio cues at the time, confining the number of sessions that can run simultaneously in the same space to one. This could be problematic in situations where the same space (i.e. a gym inside a rehabilitation clinic) is shared by more than one physiotherapist.

Haptic rhythms, on the other hand, can be directed to more than one patient simultaneously, each with their own tempo to match their cadence, without interfering with each other. This enables more efficient sharing of resources between health professionals and physiotherapists.

Cueing of each step has demonstrated stronger auditory-motor synchronisation as opposed to cueing only the paretic or non-paretic step (Roerdink *et al.*, 2011). However, designing an audio rhythm that can allow differentiating which cue is for which leg may be difficult, thus missing out on some potentially beneficial aspects of focusing attention and proprioception in gait rehabilitation. A pilot study attempting to assign cues of different pitch to each leg (Wright *et al.*, 2013), identified a number of limitations for this approach; mainly an illusion created by the pitch difference between successive cues causing an isochronous rhythm to be perceived as irregular. In addition to this acoustic illusion, participants in the same pilot study reported that having a rhythm of two tones is difficult to understand, with one participant withdrawing from the study because they “*did not like the dual-tone*”.

The haptic sense, on the other hand, has the potential to provide a more discrete solution of delivering the necessary rhythm for entrainment, while maintaining the audio channel clear, while cues can be easily assigned for each leg by changing the spatial placement of the device delivering the tactile cues.

2.7.3 Rhythmic haptic cueing for entrainment and gait rehabilitation

There is a wide literature concerning entrainment through audio rhythms, in areas such as finger tapping experiments (Repp, 2005); step in place paradigms (Wright and Elliott, 2014); and gait rehabilitation (Thaut and Rice, 2016). By contrast, discussions of haptic rhythms are mostly limited to considering their role in enhancing experiences, and interactions in conjunction with audio and/or visual cues (Elliott, Wing and Welchman, 2010).

Advances in technology mean haptic enabled devices are now widely available, with almost all wearable and holdable devices and gadgets having at least some haptic capabilities. The haptic sense has great potential for solutions to a variety of interaction design challenges. When haptics and haptic interactions are a primary means of interaction, however, the interaction is usually framed using stimulus response-models (see Figure 3 on page 14 for an illustrated example of stimulus response). In such cases, a haptic message is conveyed through a single impulse or a pattern of consecutive vibrations. The user is then expected to produce an appropriate response to the haptic message, completing the interaction. This can be a useful pattern of use of the haptic sense, with implementations including: use as a prompting device for therapy (Luster *et al.*, 2017); reduction of sensory overload in multimodal interfaces (Oakley *et al.*, 2000); or provision of an additional dimension to convey messages in safety critical systems (Politis, Brewster and Pollick, 2014).

Haptic feedback has also been used for correction of posture and technique in recreational activities such as snowboarding training (Spelmezan, 2012) or playing the violin (Van Der Linden *et al.*, 2011). By using sensors on the user's body or garments, users can have their posture monitored during the activity and vibrotactile actuators placed on appropriate locations on the body can instruct them to make appropriate corrections.

For example, in the case of violin training, the system has the ability to track a musician's violin position and bowing action in real time using motion sensors

and provides vibrotactile feedback to guide the player's movements and maintenance of the correct posture. However, interactions framed in terms of entrainment are fundamentally different: the user's response has a temporal relationship to the rhythm of the cue; allowing predictive, synchronised movement.

An example of such interaction in the music teaching domain is the work done with the 'Haptic Drum Kit' (Holland *et al.*, 2010). The 'Haptic Drum Kit' uses haptic cues on particular limbs to indicate the exact moments at which notes should be played with that limb, on a specified part of a conventional drum kit. Results from the study reported in (Holland *et al.*, 2010) indicate that novice drummers are able to learn complex drum patterns from the haptic feedback alone, although participants in the study expressed an explicit preference for haptic feedback with audio to be played. Continuing with the theme of haptic feedback for musical training, (Huang *et al.*, 2010) designed and developed a wearable device, capable of delivering vibrations on the user's fingers aiming at enhancing their piano learning experience. During this study, users who listened and felt the notes of a simple music piece were found to be able to replicate it with greater accuracy than people who just received the notes auditorily.

Studies such as the ones described in this section, reflect on the possibilities of using haptic feedback for: body posture correcting, learning simple rhythms, and controlling the movement of individual limbs in a controlled rhythmical fashion. These possibilities have also been explored for gait rehabilitation, where rhythm can have therapeutic benefits (see section 2.6).

In an early exploratory study, rhythmic haptic cueing has shown promising results and great potential, offering similar and immediate benefits to auditory cues (Holland *et al.*, 2014). This was a study involving a single stroke survivor, and in addition to gait related kinematic benefits and improvements, the participant commented on how this approach helped her posture and gait.

This early exploratory study formed the inspiration to this thesis by demonstrating how a wearable prototype, originally designed for teaching music concepts (Bouwer, Holland and Dalglish, 2013) could be used to assist people with gait related neurological conditions improve their gait, regain their mobility and independence, leading to better quality of life.

2.8 Chapter summary

Various neurological conditions, such as hemiparetic stroke, may leave patients with several gait deficiency problems. Gait deficiencies may introduce spatial and temporal asymmetries between steps leading to health problems and are associated with morbidity from various causes. Entraining to an external rhythm has shown to help patients improve their gait symmetry and assume a healthier gait pattern with immediate effect, and with evidence of longer term effects given longer term exposure.

The repetitive action of an entrained movement has also shown therapeutic permanent changes in the brain through the process known as brain plasticity (section 2.5.2). Crucially, entrainment is a different mechanism from stimulus response, with different brain mechanisms and behaviours involved, as discussed in section 2.2.3.

However, existing discussions of rhythm-based rehabilitation of neurological conditions in the literature are conducted exclusively in the context of *audio* entrainment. Audio, on the other hand, may have practical limitations, restricting its application scope within the common rehabilitation scenarios.

Haptic cueing appears to have considerable potential for cueing gait via entrainment, with several potential advantages (discussed in section 2.7.2) but has been very little studied.

The next chapter will consider in detail the research methods and approaches followed in this thesis.

Chapter 3

Research method and approach

This chapter offers an overview of the methods and research approaches used in this thesis. Very little work, beyond a single exploratory study (as discussed in chapter 2), has previously been carried out on the use of haptic cues to promote entrainment for assisting gait rehabilitation. For this reason, the research involved a variety of research approaches. There were four principal phases to the research:

- two initial formative studies to gather insights from patients and health professionals (and also to inform prototype design),
- an iterative *prototype design stage*, through which the necessary technology was developed to produce the haptic cues and monitor gait,
- a feasibility study to investigate human entrainment capabilities with haptic cues (using the finger tapping paradigm with able-bodied participants),
- a quantitative study to investigate the effect of rhythmic haptic cueing on gait symmetry of hemiparetic participants.

Consequently, a mixed methods approach was required, as detailed below.

3.1 Qualitative methods

In the first initial formative study, qualitative data in the form of in-situ observations was collected using a *contextual inquiry* based method.

Contextual inquiry was preferred over more structured methods, such as formal interviews with physiotherapists and health professionals, due to unique

circumstances surrounding physiotherapy sessions within a residential neurological care centre, where the first initial formative study took place. This context is described in more detail in in section 4.1, page 49. Physiotherapists' schedules are busy, with a combination of physiotherapy sessions, paperwork and progress reports. This made formal interview sessions with teams or individual physiotherapists impractical. On the other hand, it became clear that the physical and highly varied nature of the work meant that observing sessions in person was particularly valuable. For these reasons, observation guided by contextual inquiry principles (see section 3.1.1 below) was used. Discussions reflecting on observations were often carried out while en route between physiotherapy sessions.

The second formative study involved a *technology probe* approach. As with the first initial formative study, a number of alternative methodology options, such as participatory design workshops and structured interviews, were available. However, as this research focuses on people suffering from neurological conditions, approaches that required manual dexterity by the participant (e.g. low fidelity prototyping or even producing paper-based drawings of prototypes) were impractical. Also, many participants in this research suffered from *Aphasia*, a condition making written and verbal communication difficult (see section Hemiparetic stroke, page 51). This meant that interviews and questionnaires were similarly impractical.

The technology probe approach was chosen in recognition of the importance of allowing participants (both health professionals and people suffering from neurological conditions) to experience the technology as early as possible. Having the opportunity of this experience in using the technology helped to initiate discussions on its use, but also helped to convey the concept of haptically mediated rhythms. Discussions were typically short due to participants' aphasia related communication difficulties.

These two approaches helped to inform and frame all of the later studies. The technology probe also prompted the beginning of an iterative prototype design process for the wearable device system that would continue iterating and evolving throughout this research.

3.1.1 Contextual inquiry

Contextual inquiry is an HCI technique for collecting and interpreting data from fieldwork, with a particular emphasis on uncovering requirements for the context of use. This approach has its roots in ethnographic approaches to data gathering, and rests on four key principles: context, partnership, interpretation and focus. The paragraphs below draw on (Preece, Sharp and Rogers, 2011) (p.368):

The *context principle* highlights the importance of observations in situ, going to the place where the new technology is to be used and seeing how current practices take place. The first of the two formative studies used this principle when visiting a neurological centre to observe current gait rehabilitation techniques used by physiotherapists, as discussed in detail in Chapter 4.

The *partnership principle* proposes that designers and potential users collaborate in an equal partnership, working towards the understanding of the task through cooperation. This contrasts with conventional user observation studies, where either the designer or user typically leads the task. In both formative studies, the partnership principle was closely followed during all collaborations with stroke survivors and health professionals.

The *interpretation principle* refers to the practice of interpreting observations within the context the observation was made, rather than retrospectively forming conclusions. A straightforward way to satisfy this principle is to ask the users. In the case of the formative studies, these were survivors of neurological conditions (predominately hemiparesis) and health practitioners.

Lastly, the *focus principle* advocates keeping the focus of data gathering focused on the goals the inquiry seeks to achieve: given that contextual inquiry aims to observe users in situ, it can be easy for discussions to veer off track. Thus, in the formative studies, the overall focus was kept on activities and observations likely to help to inform techniques of gait rehabilitation via entrainment using rhythmic haptic cueing.

3.1.2 Technology probe

Technology probe is an approach broadly related to participatory design (Hutchinson *et al.*, 2003), but one where designers “seed” design discussions with a probe, usually in the form of a prototype. As noted by (Hutchinson *et al.*, 2003), technology probes:

“combine a social science goal of collecting information about the use and the users of the technology in a real-world setting, the engineering goal of field-testing the technology, and the design goal of inspiring users and designers to think of new kinds of technology to support their needs”.

During the early stages of research, it is often the case that no robust technology exists yet to present to the users.

To get around this problem, in the second formative study, as discussed in Chapter 4 (page 60), a prototype initially designed for music education purposes was used (Bouwer, Holland and Dalglish, 2013; Holland *et al.*, 2014). This prototype was capable of producing the basic functionality of the envisioned technology, facilitating discussions in context between the participating patients (stroke survivors), the health professionals and the technology designers.

Having a functioning prototype as the centrepiece of these discussions facilitated the social science goal of collecting information in a real-world setting about users and potential usage of the proposed technology. The prototype also helped the users and designers in refining design ideas. The second formative study also acted as an early field test of relevant technologies.

3.2 Iterative design process

Findings and insights gathered during the formative studies served as a starting point for an *iterative prototype design* process in which the necessary technology was refined to produce the haptic cues and monitor gait. Chapter 5 presents the iterative design process, highlighting the most important landmarks of the design process.

3.3 Quantitative methods

In the tapping paradigm study (Chapter 6) quantitative time series data was collected using a piezo-electric sensor combined with a commercial data logger, and analysed using both established (Elliott, Welchman and Wing, 2009) as well as bespoke algorithms. Full details are given in Chapter 6.

In the gait symmetry study, quantitative data was collected from two sources. The primary source was on-board motion sensors from the wearable prototype developed by the iterative design process. A supplementary source was a state of the art motion capture system in a kinematics lab in Manchester – maintained by the Manchester Metropolitan University. The gait symmetry data was analysed offline (i.e. not in real time), again, using established, as well as bespoke algorithms developed as part of this research. More on the algorithm design and data analysis techniques can be found in Chapter 5. Details on how these techniques were applied are discussed in Chapter 7.

3.4 Validity in mixed methods

Where appropriate, triangulation was used to give a more balanced and detailed picture. Triangulation is the term used for the investigation of an observed phenomenon or data outcome from a minimum of two different perspectives (Jupp, 2006). If two perspectives suggest the same result, confidence in the conclusion is increased. Four different versions of triangulation can be characterised:

- *Triangulation of data*: Data obtained from two different sources at different times, in different places from different people using (if possible) different sampling technique.
- *Investigator triangulation*: different investigators used to interpret the same set of data.
- *Triangulation of theories*: different theoretical frameworks are used to view the data or findings.
- *Methodological triangulation*: where different data gathering techniques are used.

In the gait asymmetry study, the views and opinions of health professionals were recorded and analysed whenever possible and compared against conclusions drawn from empirical analysis of the quantitative results. This facilitated investigator triangulation.

Also, in the gait asymmetry study, quantitative data from six participants in the study, as discussed in Chapter 7, page 121, were captured using two independent systems and analysed by different bespoke algorithms, thus facilitating methodological triangulation.

In both of the formative studies, exchanging detailed views in context with health professionals contributed to a milder form of triangulation less focused on final conclusions and more focused on ensuring well informed interpretation of priorities, practices and phenomena in the real-world setting.

Due to the great variability of hemiparetic participants, where appropriate, findings from quantitative data are presented for each participant individually (Chapter 7). Presenting data for individual participants along with group averages can play an important role, given the exploratory nature of this research. By grouping participant results together, it is possible to obscure significant parts of the story that may lead to valuable insights and conclusions. The next chapter will consider the two formative studies in detail.

Chapter 4

Formative studies

As described in the research approach chapter above (Chapter 3), this research began with an early exploration of the field in the form of two formative studies: an *observation* study and a *technology probe* study. Insights gathered from these initial formative studies helped with the better understanding of the gait rehabilitation field, and the familiarisation of current gait rehabilitation techniques, as well as exploring the wider physical, sensory, and cognitive issues needed to develop the system for delivering a rhythmic haptic cue for gait rehabilitation. During the course of these formative studies, a collaboration was formed between interaction designers, physiotherapists, rehabilitation experts, and stroke and brain injury survivors.

In line with contextual inquiry principles, and more specifically the *context principle*, highlighting the importance of observations in situ (discussed in Chapter 3), this early exploration of the field started with a series of *observation* visits at a specialised neurological rehabilitation centre. this early exploration of the field started with a series of *observation* visits at a specialised neurological rehabilitation centre. No specific questions or agenda was drafted prior to these visits, but insights from attending physiotherapy sessions and discussions with groups of highly trained and experienced physiotherapists led to the formulation of various questions that helped to focus the aims and outcomes from these observations (*focus principle*). In particular, after initial demonstrations, several therapists expressed the view that this approach might be suitable for a range of neurological conditions. However,

due to resource limitations and for reasons of simplicity, it was decided to focus on just one or two conditions. In making such a choice, the question naturally arose of how progress might be quantified for different conditions. This led to the formulation of two specific questions:

Qn.1. *What neurologic condition is the most suitable (or appropriate) for further investigation?*

Qn.2. *How do physiotherapists quantify progress?*

A close collaboration was also formed with the physiotherapists working at the centre's specialised units. This collaboration relationship started and carried forward as an equal partnership, with information and insights from current rehabilitation techniques, conditions affecting people's gait and ways technologies and technology interventions can be used to assist current practices being discussed between all members of the team. This collaborative attitude was motivated and supported by two of the contextual inquiry's principles: the *relationship* and *interpretation* principle.

The section below details how the observation sessions took place and their outcomes in terms of answering the questions stated above and the overall progress of this research.

4.1 Observations - Visiting a neurological care centre

Arrangements were made to visit P J Care's Eagle Wood Neurological Care Centre in Peterborough, UK. Eagle Wood contains five neurological care units, with each unit specialising in different aspects of neurological nursing needs. These include: long term neurological conditions, neuro-rehabilitation, frontal temporal dementias, learning disabilities and complex care. The centre's management and staff are keen to make research part of their practice and they are very eager to learn how they can further improve their practice and the lives of the people staying there. In consultation with the manager and the lead

physiotherapists of the centre it was decided that time could be spent visiting two of the units, as patients there were most likely to be able to benefit from the research: the neuro-rehabilitation unit and the long term neurological conditions unit.

The *neuro-rehabilitation unit*, as the name suggests, specialises in neuro-rehabilitation aiming to maximise independence of people with a variety of conditions including high spinal injury, acquired brain injury, stroke, and myasthenia gravis. Neuro-rehabilitation includes regular physiotherapy and hydrotherapy sessions, as well as occupation therapy and exercises to promote independence and overall better quality of life.

The *long term neurological conditions unit*, on the other hand, focuses on long term neurological conditions which require specialist nursing and therapy to ensure quality of life through the different stages of their condition, often leading to palliative end of life care.

These two units offered the opportunity to observe (at least) two different approaches on how health professionals approach neurological conditions; one where rehabilitation is performed to promote independence and restore patients to a certain level of mobility, and the other approach where rehabilitation cannot permanently restore mobility but aims in improving the patient's quality of life. Being a care centre, P J Care has the added advantage of most patients also being residents. This allowed for the unique opportunity to observe patients in a more day-to-day 'home' environment, and their interactions with other residents and nursing staff.

The next sections, contain experiences with patients and staff of both units, the observations made, and point out the most important conclusions allowing for informed decisions guiding the future directions of this research.

4.1.1 Neuro-rehabilitation and physiotherapy

These visits were largely exploratory, done in an informal way, with no main questions to answer, but rather aiming for the better familiarisation of the gait rehabilitation field. However, contextual inquiry principles were used to keep the observation procedures and data gathered sensible and efficient.

During the first visit, a meeting was organised with the centre's lead physiotherapists and their team to discuss the aims of this research.

The aims of this meeting were to gain a mutual understanding of what this research tries to achieve, what is required for the rehabilitation to be considered successful, and how technology can be used to enhance or assist rehabilitation methods. Physiotherapists and neuroscientists present in the meeting suggested to start by observing rehabilitation of hemiparetic stroke survivors.

Hemiparesis after stroke is common and the centre had numerous residents willing to participate in this research.

Hemiparetic stroke

Hemiparesis is characterised by weakness of one side of the body as a result of brain trauma or injury (discussed in more detail in section 2.5.1, page 27). The hemiparetic residents encountered during the visits at P J Care's Eagle Wood Neurological Care Centre were in the acute stages of their condition (stroke in this case), with minimal independent ambulatory capabilities. Physiotherapy sessions with three hemiparetic stroke survivors were observed by shadowing two of the senior physiotherapists and their teams. Physiotherapy included sessions both in the gym, and in the stroke survivor's room, with exercises promoting independence (such as laying down and getting up from bed). The gym sessions were oriented more on helping them to regain motor control and re-build lost muscle tone on their affected limbs (both legs and arms).

Mobility was a big issue for all stroke survivors with two out of the three observed not being able to make more than two steps before needing to rest.

Even then, steps were slow and difficult. Physiotherapists and their team had to physically hold the person's legs and facilitate their movement, literally putting one leg in front of the other. Interestingly, while doing that, they would also massage or tap the paretic (affected) leg during movement on the muscles and tendons, just behind the knee. According to the physiotherapists, this massaging and tapping is facilitating the muscle to initialise the movement; waking up memories in the brain of how it feels like to move. Tapping also brings attention on that leg, helping the patient to concentrate on moving it. Figure 10 shows a physiotherapist performing this action.



Figure 10 Acute stroke physiotherapy session. Physiotherapist facilitates movement by massaging the appropriate muscle and tendons, while assisting the patient to move their legs forwards by pulling their foot by the shoe laces.

In this figure, the physiotherapist holds with her right hand the stroke survivor's right (paretic) leg by the shoe laces, helping her to move forwards, while at the same time massaging her behind the knee with her left arm. A second physiotherapist is present (standing just in front of the stroke survivor to catch her in case of a fall (falls are a common occurrence amongst people suffering from gait related deficiencies).

Rehabilitation in the gym also included stroke survivors walking while supporting themselves between parallel bars and using a stationary pedal machine (see Figure 11) to increase leg muscle tone – a common concern in stroke survivors.

With deficiencies in motor control and general loss of sensitivity on one leg, stroke survivors often do not trust their affected leg. This loss of trust makes them try and spend as little time on it as possible. Underusing the affected leg causes it to weaken, losing muscle tone and bone mineral density (an issue discussed in section 2.5.1). One analogy a physiotherapist used to explain the situation is: “[...] imagine standing on leg. Then try to take a step forward. This is how most stroke survivors feel”.

Using a pedal machine (Figure 11), the stroke survivors could get a good exercise through the rehabilitation and physiotherapy session, but the physiotherapist could also assess their strength and strength asymmetry. The machine is capable of monitoring how hard each pedal is pushed, and can monitor and quantify progress in terms of strength symmetry between the legs.

After the pedal machine sessions ended, the physiotherapists emphasised how important it is to restore symmetry between the two legs. These observations agree with the literature on symmetry and the importance of gaining and maintaining a healthy gait pattern.



Figure 11 (Left) The gym space with the parallel bars where most physiotherapy sessions take place. (Right) Pedal machine designed to be wheelchair accessible.

Another interesting observation came from an interaction between the physiotherapists and one of the stroke survivors. Just before a physiotherapy session, the stroke survivor kept asking for her glasses. The physiotherapist

then went away and returned with her walking shoes and told her that these are shoes and not glasses. After the event, the physiotherapist explained that this is one way that a stroke may “short circuit” parts of the brain, causing stray connections to form in a condition known as *Aphasia* (Cohen, 1999). This is a relatively common issue stroke survivors face, especially during the acute stages, where descriptions and descriptive language gets mixed up in their brain, and objects are associated with the wrong words. The patient never wore glasses.

4.1.2 Long term neurological conditions

Huntington's disease

Eagle Wood neurological centre also deals with residents with long term neurological conditions, such as *Huntington's disease* (HD). HD is an inherited genetic disorder of the central nervous system. More specifically, HD damages specific nerve cells in the central nervous system and affects movement, cognition (perception, awareness, thinking, judgement) and behaviour. The damage gets progressively worse over time until HD sufferers are left totally dependent and require full nursing care. Death is usually from a secondary cause, such as heart failure, pneumonia or another infection. Sadly, there is no known cure and HD's progress cannot be reversed or slowed down. The only form of physiotherapy residents with Huntington's receive is for improving their quality of life by managing the symptoms of their condition.

While visiting Eagle Wood, there was a chance to meet three residents with HD. As most people with HD, they suffer from erratic muscle movements, causing them to frequently lose their balance and fall. The two older residents adopted a strategy of walking in which they keep their legs slightly spread apart, giving them a larger base. However, the youngest of the three has a very atypical way of walk where she is constantly walking on the tips of her toes,

being, as one of the physiotherapists described, in a “*constant free fall; shifting her weight forward and then catching herself before she’d fall*”.

Unsurprisingly, this makes her extremely prone to falls, regularly injuring herself. After conversations with on-site physiotherapists and carers, it was concluded that having something that would bring the attention to her legs, and maybe slow her down, has the potential to make her think about the next step, and be beneficial. Even though HD was eventually excluded from the scope of this thesis, the implications of rhythmic haptic cueing to HD patients’ quality of life will be considered in the future (see Future works on page 163).

Parkinson’s disease

P J Care’s Eagle Wood neurological centre did not have any residents with Parkinson’s disease (PD) at the time of these visits. However, discussions with physiotherapists and health professionals at the centre included the treatment PD patients receive.

PD has complex implications to the way someone walks, with one of the most common described as “freeze of gait” (FoG). During a FoG incident, the patient’s muscles tense and the individual is suddenly immobilised (freeze). If that happens during walk, it could lead to a fall, causing serious injuries. It is not clear exactly when or what triggers a FoG, making it extremely difficult to predict and even more difficult to prevent. Interestingly, by bringing the attention on the frozen limb (by tapping on it for example) it may cause it to unfreeze. On the other hand, tapping on a leg that is behaving normally may cause it to freeze, triggering a fall. This raised concerns, as the prototype system for this research is using haptic vibrations that could potentially trigger a FoG instead of preventing it.

Discussions with health practitioners also suggested that the medication PD patients are prescribed with to manage tremor has a half-life (time before the medication’s effectiveness is halved) of a few hours, which, could also depend

on the person's mood and meals before and after taking it. This would, in long term, make it difficult to assess if any changes observed on the way a PD patient walks was a result of walking in the rhythm, or if it was because their medication effectiveness was running out.

4.1.3 Hydrotherapy sessions

The walking ability of people affected from neurological conditions is often significantly improved when walking in the water. The buoyancy of the human body makes it easier for people lacking the physical strength to support their body weight due to a neurological condition, to stand up and receive rehabilitation for their condition. This is an interesting observation and has the potential of expanding the range of patients and conditions where this research can be applied to.

Eagle Wood neurological centre runs hydrotherapy sessions in a shallow heated pool (see Figure 12). Resident patients go in the pool with one or two physiotherapists (at least three in the room at any time for safety) and perform a series of exercises depending on their condition. Exercises include walking the length or diagonal length of the pool, walking holding floating devices, and squatting while holding the pools edge. These exercises are designed to facilitate lower limb motion.

Three hydrotherapy sessions were observed: one with an acute stroke survivor (also observed during gym rehabilitation – discussed in section above), one with a cancer survivor that left her with gait deficiencies, and one with a resident with Guillain-Barré syndrome; a disorder where the body's immune system attacks part of the peripheral nervous system affecting motor control of both upper and lower limbs (Cohen, 1999).

All residents in the hydrotherapy sessions observed found it extremely difficult to walk outside the water; especially the Guillain-Barré syndrome patient, who was completely dependent on an electric wheelchair. However, once in the

water, they could all walk without needing their physiotherapists physically supporting them. This is an important observation as these patients had the motor control to take steps forwards and walk inside the pool. However, they lacked the physical strength, fine-tuned balance and sometimes, according to their physiotherapists, confidence to even attempt to walk outside the pool, highlighting the importance of confidence and physical strength during gait rehabilitation.



Figure 12 Hydrotherapy session Guillain-Barré syndrome patient. Patient is wheelchair bound, however in the water, due to buoyancy effects, he can walk unsupported.

4.1.4 Conclusions from observations

Observation sessions provided evidence to answer the questions stated at the beginning of this chapter. The first question asked:

Qn.1. *What neurologic condition is the most suitable (or appropriate) for further investigation?*

The therapists pointed out that of the neurological conditions affecting gait, hemiparetic stroke was the most frequently occurring. Furthermore, given that hemiparesis affects symmetry, their opinion was that this seemed the most suitable focus for further investigation.

Consequently, a decision was made to focus on hemiparesis; with the most suitable candidates being *stroke and brain injury survivors with chronic*

hemiparesis and enough mobility to be considered *independent community ambulators* (i.e. be able to walk independently and without physical support from another person).

In dialog with the therapists, it was further noted that stroke survivors, unlike Parkinson's patients, for example, are not dependent on medication to manage their symptoms and motor control issues. Therefore, findings could be reported with more confidence as being caused by the proposed technology intervention instead of an external factor, such as a medication's half-life.

Another factor emerging from the discussions was that hemiparesis after stroke tends to be stable, with survivors not showing any neurological degeneration over time, unlike in the case of Huntington's disease and Parkinson's patients. So again, findings could be clearer to attribute to the intervention rather than an external factor.

From observations during the physiotherapy, it became apparent that the physiotherapy intervention proposed is unsuitable for stroke survivors who are still in their acute stages of recovery. It became clear that following a rhythm and trying to time their steps is typically not possible in the early stages following a stroke. Walking to a rhythm, on the other hand, is more suitable for people who have recovered some mobility following these acute stages.

The observations and subsequent discussions with physiotherapists also helped to answer the second question:

Qn.2. How do physiotherapists quantify progress?

The answers to this question varied depending on the specific needs of each patient, and the condition in question. As PJ Care is a neuro-rehabilitation clinic, most resident patients are in the acute stages of their conditions. In the case of stroke survivors, for example, therapists noted that progress might be quantified in terms such as two more consecutive steps than the previous therapy session. As noted in the sections above, therapists often direct the use

of equipment such as pedal machines for exercise. This machine has the capability of displaying the force a patient is pushing each pedal with and the symmetry between the two legs. Therapists often record such measures as an indication of progress between sessions.

Useful observations were also made during hydrotherapy sessions aiming for gait and movement rehabilitation. Therapists pointed out that hydrotherapy rehabilitation sessions involving walking in water can alleviate some physical deficits while at the same time being safer as there is no serious risk of injury from falls, increasing the patient's confidence to walk unsupported. This suggested possible directions for technologically assisted interventions, however, designing a technology to work inside or under water would be challenging as there are numerous safety considerations wherever electronics and water mix, and walking in a pool would add to the complexity of gait monitoring.

Lastly, discussions with therapists focused on speech and language deficiencies observed when talking with stroke survivors in the centre's residential common area. These deficiencies are a result of a condition known as *Aphasia*, common in stroke survivors. Aphasia is a speech and language impairment where words and their semantic meaning are mixed in the brain. Most of the time, aphasia has no cognitive implications, however it may prevent patients from expressing or structuring their thoughts in a coherent manner. Therapists also noted that aphasia can also affect the way patients comprehend instruction. Therefore, this is something that needs consideration when designing studies concerning stroke survivors (such as the studies discussed in section 4.2 below and in Chapter 7).

The section below describes a technology probe study conducted shortly after the observations at the neurological rehabilitation centre, involving a group of stroke survivors with independent ambulatory capabilities and a group of

physiotherapy experts from the Manchester Metropolitan University. This study builds on the conclusions and insights of the observation sessions.

4.2 Technology probe study

In the light of the findings from the previous exploratory study presented in section 4.1, this study is aimed at exploring the wider physical, sensory, and cognitive issues needed to develop the system for delivering a rhythmic haptic cue for gait rehabilitation, through collaboration between interaction designers, physiotherapists, rehabilitation experts, and stroke survivors.

4.2.1 Methodology

This study applied a technology probe methodology (discussed in section 3.1.2, page 44) to gain insights into design issues, through collaboration between interaction designers, physiotherapists, rehabilitation experts, and stroke survivors. The study itself had a user centred approach, having the real users and their goals as the driving force; not just the technology. Contextual inquiry principles (page 43) were also used to frame the data gathered, facilitate discussions and maintain focus.

Stroke survivors participating in this study were asked to use a wearable prototype, capable of producing rhythmic vibrations on alternating legs (more in section 4.2.4 below) and walk synchronising their steps to the beats of the rhythm. While using the technology, discussions between everybody involved in this study were encouraged. The stroke survivors, health professionals, and the technology designers, all had the chance to exchange ideas and experiences from the new technology.

The aim of these discussions was primarily to investigate issues relevant to the conception and implementation of a technology aiming to assist gait rehabilitation. Ultimately, findings from this study helped in initialising the

first iteration of a wearable system, capable of producing a steady rhythm of haptic cues for gait rehabilitation.

Specifically, this study aimed to gain insights from stroke survivors and health professionals on:

- the location, strength, and rhythmic timing of the haptic cues;
- the participants' initial reaction to the cues;
- design suggestions.

The study also aimed to obtain a first understanding on difficulties hemiparetic stroke survivors may face in their day-to-day routine. These findings along with some unexpected discoveries, such as the language used to describe the haptic cues, are itemised and discussed in section 4.2.5.

4.2.2 Participants

Through observations, discussed in section 4.1 above, hemiparetic stroke survivors in the chronic stages of their condition, were identified as a suitable target group for further investigation in this thesis.

Four community-dwelling adults (one female) with chronic hemiparesis (chronic defined as more than 6 months since stroke onset), gave written informed consent to participate. The time since each individual's stroke incident varied from 5 to 42 years (see Table 1).

Participant code	Age / Sex	Stroke onset (years)	Paretic side
P1	57 (Male)	10	Right
P2	46 (Female)	13	Right
P3	68 (Male)	42	Right
P4	63 (Male)	5	Right

Table 1 Participant demographic information

All participants recovered the ability to speak, although still with some difficulty. All could walk unaided, but not for very long, and similarly with

some difficulty. They were highly motivated participants who regularly participate in research projects and are much at ease with the physiotherapists, other staff, and lab setting. All participants were ready to give honest critical opinions and some participants had become good friends over the years because of their stroke and their participation in various initiatives to support stroke survivors.

In addition to stroke survivors, a team of health practitioners and researchers from the Manchester Metropolitan University was also invited to take part by participating in discussions and giving their expert opinions on observations and findings made during this study. This team included a professor of nursing and two experienced physiotherapists.

4.2.3 Apparatus

As described at the beginning of this section, and in detail in section 4.2.1, the methodology for this study is a technology probe using the wearable devices noted in section 4.2.3 and described in detail in section 5.1, page 75. These wearable devices were an early prototype, initially designed for music education purposes (Bouwer, Holland and Dalglish, 2013; Holland *et al.*, 2014); however they were more than capable of producing the basic functionality of the envisioned technology, facilitating discussions in context between the participating patients (stroke survivors), the health professionals and the technology designers.

4.2.4 Procedure

The sessions were spread out over three days and were arranged in such a way that participants were not expected to do too much walking in one day. As part of this study, kinematic data was also recorded for each participant, not with a specific aim in mind but rather as a test to the capabilities of the lab's newly installed Qualisys optical motion capture system. This kinematics data

collection did not interfere with the findings and conclusions of the present study.

Participants were asked to walk the length of the room four to six times (depending on each individual's walk ability and stamina) in three conditions: baseline (without cue), with cue, and without cue again. This procedure also served as an early pilot to the study discussed in Chapter 7.

During the first day, an early version of the wearable technology – called the *Haptic Bracelets*, initially designed for an unrelated to gait rehabilitation music purposes, but with the ability to produce precise haptic rhythms, was presented to participants (see section 5.1, page 75 for more details on the technology).

This meeting in the first day allowed participants to get an early feel of the technology and for researchers to get initial feedback on its design. In addition, it was a chance to discuss the aims of this research with the physiotherapists taking part in this research and share ideas and concerns, collaborating towards a common goal; using technology to assist and enhance current gait rehabilitation, and setting the scene of an equal partnership, a key principle of contextual inquiry methodology.

On the second day, the first two of the participants, and on the third day the second two participants took part in structured hands-on sessions with the technology.

At the start of each session, equipment was setup and participants changed from their normal clothes into shorts to allow reflective markers used by the external motion capture system to be clearly placed. The wearable devices were then strapped on to both legs of each participant using Velcro straps. During the setting up period there were informal conversations with participants, checking that they were comfortable with the set-up. Issues emerging from the exact placement of the vibrotactiles are considered in section 4.2.5 below.

Baseline and rhythm familiarisation

Participants were asked to walk, as they would normally do from a ‘start’ marker on the floor to a ‘finish’ marker at the other side of the room. Walking from start to finish and then from finish to start counted as two trials. A chair was provided at either end for participants to rest whenever they needed.

After completing the first set of trials without haptic cueing (baseline), the tactile metronome of the Haptic Bracelets was switched on. Initially, participants were asked simply to sit on a chair and feel the buzzes. The tactile buzz intensity was adjusted so that pulses could be felt clearly but without causing any discomfort. This intensity adjustment was important as some stroke survivors also suffer from sensory deficiencies on the skin.

Once the intensity was set to a comfortable level, the period of the metronome buzz was adjusted for every participant to match his or her natural walking speed, as calculated from the baseline condition. Setting the metronome’s period to match the individual’s natural walking rhythm is important for rhythm based gait rehabilitation as it was found to help participants feel more comfortable in timing their steps to the beats of the rhythm (Thaut and Rice, 2016).

Once the tactile intensity and the metronome period was adjusted, the participants were asked to stand up and try to step in place following the metronome’s rhythm. At this stage participants were asked again if they felt like they needed any further adjustments to be made on the metronome period or the vibrotactile intensity. Throughout this familiarisation stage, participants were asked about their initial thoughts, starting conversations around the technology, the rhythm, and the haptic cues (see Figure 13).

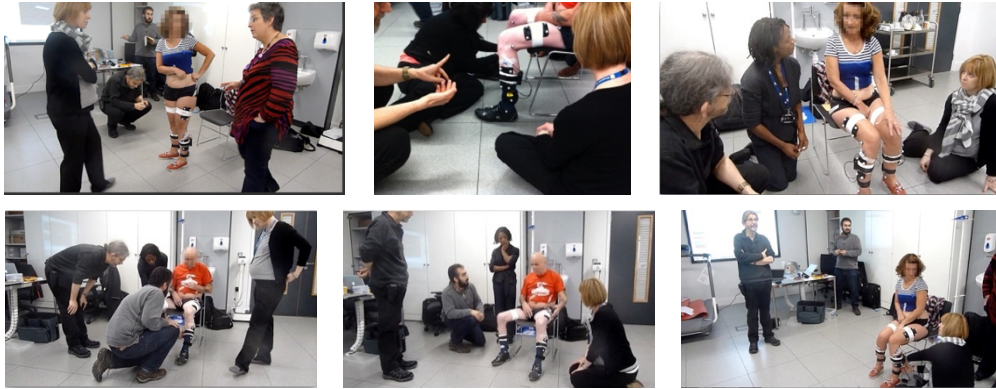


Figure 13 Images from discussion sessions with stroke survivors and physiotherapy practitioners during and after interacting with the technology.

Walking with cue

When the participants confirmed they were ready to proceed, they were asked to walk following the haptic rhythm. The instructions on how to follow the haptic rhythm were intentionally vague in order to allow a range of behaviours. However, this instruction was later found to have several limitations, not allowing the participants to fully understand the task, and was subsequently refined for the final study discussed in Chapter 7, page 121.

After completing six trials with the cue, participants were given a short break before being asked to walk through the length of the space for a further six trials without the cue, as they did in the baseline session; but this time while trying to walk to the rhythm from memory. This allowed for the investigation if participants could still remember the rhythm shortly after being exposed to it and therefore indicate lasting entrainment effects. Implications of the rhythm's lasting effects are discussed in the Discussion section in page 71 of this chapter.

4.2.5 Findings

Location, strength and timing of cues

Although, initially all participants were asked to wear two Haptic Bracelets (one on each leg), there was some variation in how participants responded to the suggestion. In the event, all participants accepted the initial suggestion, except a single participant (P1), who chose to wear a single bracelet on a single leg. He explained that he found it difficult to switch attention between legs fast enough. Interestingly, he chose to place the vibrotactile on his affected leg, even though this had much less sensitivity (more on this below). He felt that by focusing on that weaker leg it helped him to pay attention to it.

All survivors had a greater or lesser degree of spatial (i.e. step lengths) and temporal (i.e. time between steps) asymmetry between the affected and non-affected leg. Generally, as one of the physiotherapists present later explained, survivors try to spend as little time as possible on their affected side, simply because they “*don’t trust it enough*”. Having lost sensitivity on the affected limb, and considering the consequent motor deficiencies stroke survivors experience, they often lack the confidence to rely on it for supporting their weight and try to get off it and step on the non-affected limb, they now trust more, as soon as possible. This is causing a distinct hemiparetic gait pattern and gait asymmetries (hemiparetic gait discussed on section 2.5.1 page 27). Reduction in asymmetries, approaching what is defined as the normative level (Patterson *et al.*, 2008) is often the required outcome and one of the main aims of gait rehabilitation.

During this study, the exact placement of the vibrotactiles was decided by the physiotherapists. Specifically, on site physiotherapists suggested to tape the vibrotactiles on the tibialis anterior muscle (see Figure 14) near the knee using surgical tape. They felt that this placement was most likely to stimulate appropriate movement autonomously. This choice raised questions of balancing the notion of entrainment with elements of stimulus response. As discussed on section 2.6.1, page 30, rhythmic audio stimulation is known to yield immediate improvements to gait through entrainment.



Figure 14 Tibialis anterior muscle. Physiotherapy experts suggested delivery of haptic cues on this muscle, near the knee.

The choice by the physiotherapists of placing the vibrotactiles on the tibialis anterior muscle represents a line of thought that contrasts with straightforward entrainment, and may be a choice influenced by current gait rehabilitation techniques that involve stimulating the muscles by gently massaging them; a technique observed earlier and is described in section 4.1.1 page 51. The apparent conflation of notions of stimulus-response by massaging muscles to directly facilitate movement, and entrainment for regulating movement patterns is further explored in the discussion section below.

Issues concerning sensitivity and intensity also raised questions. Rhythms need to be provided with sufficient intensity to allow participants to sense and entrain to them. The vibrotactile intensity therefore had to be strong enough to be readily felt, but gentle enough to be comfortable and pleasant for extended periods of time. Unsurprisingly, the levels required to achieve this balance varied considerably between some of the participants. Three out of the four participants preferred the intensity levels at about 40% intensity. However, one participant (P1) had lost 75% sensitivity from his affected leg (sensitivity measured by an on-site clinician using standardised tests), and so requested

maximum intensity of the tactile cue to allow him to be able to feel the tactile signal on that leg. Aside from P1, who eventually opted to use a single bracelet, all participants reported finding a suitable balance in intensity after appropriate adjustment.

Reactions to the haptic cues

After trying out the haptic metronome all participants agreed that it gave them a rhythm to walk to. As P4 said, *“The beat (rhythm) is, it’s something to listen to. [...] the rhythm is good for me.”*

An interesting observation came from the comments of one participant, P1. Before sustaining his stroke, he was in the army. During discussion, he talked in detail how the rhythmic haptic cue he felt on his leg reminded him of marching in the army. *“I remember being in the Army. [...] even in your sleep could do it (marching). But now it’s been a long time. It comes back to me. [...] I thought, hang on, me in the Army, doing it, and then it shut up (mentally blocked out) everyone there, that one comes up. 1, 2, 3 and that thing goes 1, 2, 3...”* (P1). The rhythmic cueing seemed to wake up a long-lost memory and helped him “march” in rhythm; *“my mind’s coming back from the Army”* (P1).

Another effect that was observed was the rhythm staying in the participants’ head for at least fifteen minutes after the haptic metronome was switched off (time from switching off the haptic metronome to time of discussion session). All four participants mentioned this phenomenon. *“If it is switched off [...], it’s still there. [...] in my head”* (P4). These observations suggest that participants were readily able to entrain mentally, and it provides evidence of rhythm persistence when entrained to a haptic rhythm.

Language used

Participants in this study frequently used “hear”, “listen” and other audio related descriptors to describe feeling the cues delivered by the tactile

metronome. For example, P4, stated: *“The beat is, it’s something to listen to”*. These terminological habits have been noted elsewhere in speech about *heard*, rather than *felt* haptic cues (Bouwer, Holland and Dalglish, 2013).

Design suggestions from participants

The discussions during and at the end of this study, facilitated in the better understanding of what stroke survivors need, what features the wearable devices should have and how they should look.

One point arising from all discussions was the participants’ scepticism of using an unaltered beat, or indeed any regular beat outside the lab or rehabilitation clinic and on uneven surfaces and badly maintained pavements; “[...] *where I live there’s nothing flat.*” (P1) “[...] *the pavements, I have to think about the pavements*” (P2). All participants agreed that it would be very difficult to maintain a rhythm while negotiating a “difficult” walking surface. The option of having a way to manually adjust cadence settings in such situations was quickly dismissed as being too difficult. Participants commented that the mental burden is already too high while walking without trying to maintain a rhythm. Having to calculate adjustments would only add to that burden. One participant (P2) commented that she had only recently trained herself in walking and talking at the same time showing the difficulties and mental burden, some stroke survivors endure during walk. *“I used to not be talking while I was walking because I may fall over [...] [now] I [walk and] talk a lot”* (P2).

The only universally accepted option was to be able to switch the metronome off whenever they felt like it was unsuitable or too difficult to follow safely.

Other design issues considered included the device’s size and conspicuousness. A small, light size was felt extremely important, as users would be wearing them for extended periods of time. Also, three out of the four participants agreed that they wanted the devices to be as inconspicuous as possible. P3

notes: “*You don’t want to feel that it’s something that people will stare at you because you’ve got these things on*”.

Finally, a stroke often causes survivors to lose control of the arm on their paretic side. That means they may experience difficulties in strapping the devices on their legs, therefore special considerations need to be taken when designing the straps.

Attitudes of participants

All four participants indicated that their motivation for participation was to help recent or future stroke survivors: as stroke survivors with chronic hemiparesis, they appeared dubious about the likelihood of any intervention improving their own condition. For example, P2 noted: “*Maybe earlier, maybe, I don’t know, because I’ve had my stroke for such a long time (13 years), I don’t know.*” Interestingly, the same participant later described how she had recently re-learned how to walk on sand. “[...] *I’ve just learnt how to walk on sand. You know, that’s, I’ve learnt and adapted myself to walking on sand. [...] I learned] new strategies [...] a few years ago I couldn’t walk on grass and now I can slowly.*” Thus, despite expressing pessimistic views, there was evidence of learning to adapt to new situations and developing improved strategies for walking.

Observations by participants on everyday difficulties

The interview session at the end of the walking trials provided rich information regarding difficulties faced in everyday life in walking after a stroke.

As already noted, the unevenness of the pavements was a common practical problem mentioned by all four participants. “*Where I live there’s nothing flat*” (P1). Having to walk on uneven surfaces is very important for people who already have to put a great amount of effort to coordinate their legs and walk. “*I have to think about the pavements*” (P2). “[...] *instead of looking ahead to*

the distance you are constantly watching where you are putting your feet you know, more conscious of that factor.” (P3)

Participants noted that the situation is made worse when they have to cross the road or when they carry things (e.g. groceries), having to actively shift their balance on one side to compensate. The above points have design implications, as considered in the discussion section below.

4.2.6 Discussion

Unsurprisingly, different participants preferred different absolute vibrotactile intensities, ranging from around 40% intensity to 100% intensity. However, more interesting issues emerged concerning the balance of intensities between the paretic and non-paretic legs. For example, in his initial attempts, participant P1 preferred very disparate vibrotactile intensities for his two legs, due to a 75% loss of sensitivity in the affected leg. One might expect that such a disparity could be addressed simply by turning up the vibrotactile intensity on the affected leg. However, after P1’s initial attempt to walk with a vibrotactile device on each leg, he found it difficult to switch attention between legs fast enough and chose to switch to a single vibrotactile on the paretic leg.

This raises several interesting issues. Where entrainment has been established, conscious attention is not generally required to be aware of the timing of the next beat. The situation is different when entrainment is in the process of being established, and of course in the case of stimulus response. However, the use of haptic cues to direct attention, or to focus proprioception as possible avenues for influencing gait merits investigation.

Due to P1’s condition, it was not possible to clarify his observation fully. For example, it would be useful to distinguish between issues of attention switching versus possible sensory issues. Certainly, especially for any situation in which a limb has lost much of its sensitivity, this issue deserves closer study.

One interesting design issue is an apparent tension between the notion of entrainment, and the notion of stimulus response, as noted earlier. Some ramifications of this tension did not become apparent until reflecting on the findings of the study. Previous studies in the audio cueing of gait such as the ones summarised in (Thaut and Abiru, 2010), and discussed in Chapter 2, strongly suggest that entrainment is central to metronomic gait rehabilitation.

By contrast, in the more exploratory present study, with the explicit aim of eliciting views from end users and professionals from several disciplines, the deliberate openness of the instructions seems to have been interpreted by participants in ways different from the stricter procedures used in the previous studies mentioned above. Entrainment to the haptic rhythm and investigating the effects of entrainment to hemiparetic gait was not investigated in this study.

As previously noted, the physiotherapists in the present study chose specifically to locate the vibrotactiles on the tibialis anterior muscle near the knee, spurred by the idea that timely action might be stimulated, which seems to suggest the idea of stimulus response. This seems to have been motivated in part by physiotherapists' use of the touch of their hands to assist with gait rehabilitation and facilitate muscle movement (see section 4.1 Observations - Visiting a neurological care centre – page 49). The choice of placement may also have been motivated in part by analogy with FES (Functional Electrical Stimulation) devices, which are used by some hemiparetic patients (though none in the present study). These devices typically employ a sensor worn on the base of the foot to instruct the FES to directly stimulate the relevant muscle by passing a small current through it causing it to contract and avoid “foot drop” (a condition where the toes do not lift sufficiently high off the ground during each step), which can otherwise cause stumbling. However, the FES does not give a metronomic cue, rather it is tied directly to the wearer's steps, whenever they may occur.

Despite all the above considerations, at least three participants explicitly noted that the rhythm would remain in their heads for some time after the haptic metronome was switched off. Participants said they could still “hear it” in their head and that it gave them “*something to listen to*” while walking. Perhaps most interestingly, P1, said that the haptic metronome woke forgotten memories of marching in the army, and that this helped him maintain a rhythm while walking.

It may well be that for different aspects of rehabilitation, both entrainment and stimulus-response are valuable. Physiotherapists and interaction designers, together with stroke survivors are likely to benefit from working together to understand how these approaches relate, and which are most relevant in what circumstances.

4.2.7 Study limitations

At the time of the study, a force plate (for measuring the impact of steps) was in the process of being installed in the lab, but its cover was not yet fitted, exposing the plate surface, which lay at a lower level than the rest of the floor. This exposed plate surface can be seen in Figure 15 below (blue tiles).

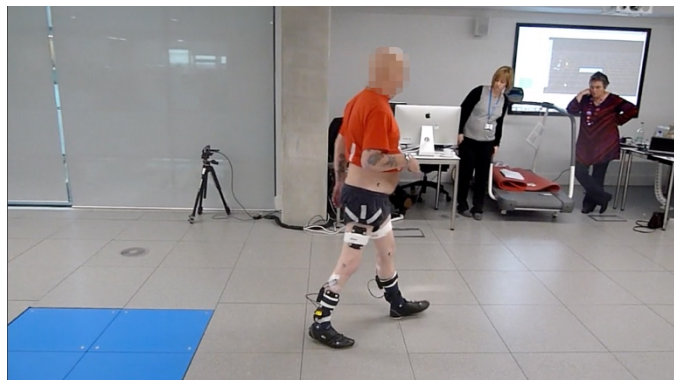


Figure 15 Participant using the technology during the technology probe study. Exposed force plate can be seen in the lower left corner of the image.

Due to the shape of the lab, participants could not easily avoid stepping on the plate and were forced to adjust their gait to step on the plate squarely. This

tended to disrupt their gait but did not interfere with the aims of this formative technology probe study. The exposed plate was covered for the subsequent study discussed in Chapter 7, page 121. The right part of Figure 46 on page 132 shows the new lab configuration with the force plate now hidden under normal floor tiles.

4.2.8 Conclusions from technology probe

In this study, the main aim was to identify issues with implications for design at disparate levels of specificity and abstraction. Several promising directions were identified. For example, the design tensions between vibrotactile placement and entrainment versus stimulus response, and the related rhythm persistence. These all deserve careful further investigation and are explored in the subsequent study in Chapter 7.

Findings on what is required also included cosmetic aspects such as a small, inconspicuous device that can easily be hidden under normal clothes, and practical considerations such as the way the devices are strapped on the patient's body. Design issues considered in the "Findings" section (page 66) and discussed in the "Discussion" section (page 71) helped to start the iterative prototype design and development process (considered in Chapter 5). These findings were also considered when designing the study discussed in Chapter 7, page 121.

Chapter 5

System design: The Haptic Bracelets

The previous chapters motivated and contextualised the approach of rhythmic haptic cueing for gait rehabilitation. Walking following an external metronomic rhythm has been shown to improve gait (section 2.6), leading people with neurological gait deficits to walk more symmetrically and to neglect their affected leg less.

This chapter focuses on the development and implementation of a wearable prototype system, capable of delivering a steady haptic rhythm and monitoring gait by recording movement. The development was an iterative process, driven by observations and insights gained during the formative stages of this research as discussed in Chapter 4, continual lab testing, and pilot evaluation sessions. The chapter starts with a quick overview of a pre-existing system. This pre-existing system was used as a technology probe in section 4.2, page 60 and played a crucial role in motivating this research. Section 5.2 proceeds to describe the operation concept behind the prototype system before explaining the system's implementation in section 5.3.

5.1 Historic reference: naming the Haptic Bracelets

To some readers, the name “Haptic Bracelet” may be strange. Even though a bracelet can technically, and by definition, be worn on the ankle, it is usually associated more with the wrist or the arm. The name “Haptic Bracelet”

however comes from an earlier version of the system, primarily designed and developed for teaching multi-limb rhythms - such as encountered when playing the drums – for musicians and music learners. Initially, a wired version called “the Haptic Drum Kit” (seen in Figure 16) employed four computer-controlled vibrotactile devices, one attached to each wrist and ankle (Holland *et al.*, 2010). Precisely planned haptic cues were used to guide the playing of rhythmic patterns on a drum kit that required multi-limb co-ordination.

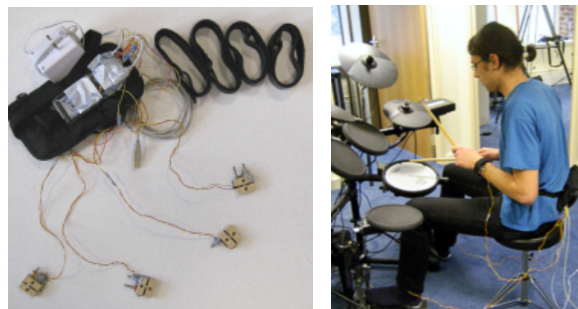


Figure 16 The Haptic Drum Kit.

The main aim of the Haptic Drum Kit was to promote rhythm skills and multi-limb coordination. After some initial studies (Holland *et al.*, 2010), the kit evolved to a more wearable version (Figure 17) with extended functionality such as teacher-student pairing (Bouwer, Holland and Dalglish, 2013) and real-time analysis of MIDI music files for haptic play-back (Bouwer, Holland and Dalglish, 2013). This new wearable iteration, including a wireless version (Holland *et al.*, 2014), was re-named as the “Haptic Bracelets”.



Figure 17 Earlier version of the Haptic Bracelets designed and implemented for music applications.

This name was kept for the new prototype system as an homage to the early work using the devices. Although this “older” version of the device is able to produce and maintain a steady tactile rhythm, it was past its prototype stage: the hardware component of the device was finalised and a custom printed circuit board was manufactured for it. This meant the devices contained electronic components that were either not needed or did not allow for efficient gait monitoring, as required by the current study on gait rehabilitation, adding unnecessary weight, bulk, and complexity to the system.

Therefore, instead of attempting to adapt the older version to fit the new purpose of gait rehabilitation, a decision was made for a complete hardware and software redesign of the system. From this point onwards, the name “Haptic Bracelets” will be used to refer to this new, redesigned wearable system.

5.2 The Haptic Bracelet system for gait rehabilitation

5.2.1 Prototype system concept

The concept of the Haptic Bracelet system is based on the natural phenomenon of entrainment (discussed in detail in Chapter 2), and a need identified during the literature review and formative studies (Chapter 4) of characterising gait and gait related progress for assessment and communication purposes.

Therefore, the prototype system concept can be summarised as having two main aims, to:

- **produce a steady haptic rhythm**, helping entrainment between the rhythm and the wearer’s gait cycle;
- **monitor and analyse gait characteristics**, allowing for a meaningful gait assessment.

The first aim is based on findings from the literature showing that entrainment of movement to steady rhythms of isochronous beats is possible, with

significant therapeutic benefits to gait rehabilitation progress of hemiparetic patients – the target user group in this thesis.

As discussed in Chapter 2, entrainment can readily occur between independent rhythmic processes provided a weak link exists between them. In the case of neural entrainment, as used in movement rehabilitation, the two independent rhythmic processes are: the external rhythm and the rhythmic action (i.e. gait in this case). The weak link between the two processes is provided by the brain and neural network used for sensing the rhythm and initiating the action. (As the term entrainment is generally used in physics, one would expect the link to be two-way; however, as used in rehabilitation contexts, the term is conventionally used with one-way links). Entraining movement with an external rhythm showed significant immediate and long-term benefits in patient's walking patterns. Specifically, the use of audio rhythms for gait rehabilitation of neurological conditions has been widely explored showing significant benefits to spatial and temporal gait characteristics as well as gait related symmetries.

Entrainment of gait occurs easily to steady rhythms of isochronous beats when the rhythm's tempo is similar to the person's preferred cadence (Roerdink *et al.*, 2011), with higher therapy benefits observed if both legs are cued (Roerdink *et al.*, 2009). However, attempts to assign rhythmic *audio* cues to each leg independently (separated by pitch) were not very successful due to limitations in the way audio is perceived (Wright *et al.*, 2013).

The approach used in this thesis uses isochronous sequences of *haptic* cues as the external rhythm instead of audio, as haptic rhythms may have certain practical advantages over audio rhythms, when considered within the context of gait rehabilitation - an argument discussed in section 2.7.2.

One such advantage lies in the nature of the haptic sense. People are readily able to sense to which limb a haptic cue is being applied. However, off-the-

shelf haptic devices, capable of producing a haptic rhythm through tactile cues, are not usually capable of providing cues in different locations at different, but carefully synchronised, times. Therefore, the Haptic Bracelet prototype system has to be capable of producing a multilimb tactile metronome; producing tactile cues on alternating legs. This will allow for cueing each limb independently, overcoming the limitations identified in the previously mentioned audio based study (Wright *et al.*, 2013) while also facilitating the investigation of attention and proprioception in the context of gait rehabilitation.

A second design aim for the prototype is based variously on: insights from the literature (Chapter 2); discussions with health professionals; and observations of gait rehabilitation techniques made during the formative studies (Chapter 4). Health professionals often need to quantify a patient's gait for reasons of assessment and better communication with other health professionals. However, they often rely on semi-subjective tests and technologies that are either limited in their descriptive capacity or overly expensive, involving specialised installations and high running costs. Therefore, the new prototype system aims to monitor gait and extract meaningful temporal and symmetry related gait characteristics in categories suitable for health professionals.

As discussed earlier in this section, the system uses a multilimb approach, where one device is placed on each leg to promote entrainment via rhythmic haptic cueing. This has the extra advantage of motion data being gathered from each leg independently. Having data from each leg makes it possible to easily identify data from the paretic leg (affected by the neurological condition) and non-paretic leg, increasing the efficiency of the analysis of temporal characteristics and asymmetry values.

In summary, to address these aims, the system consists of:

- a **set of wearable devices** (one for each leg), capable of producing haptic cues in the form of short vibrations, and monitoring gait;
- a **central control unit (CCU)**, capable of controlling the wearable devices, arranging their vibration patterns to form a steady isochronous rhythm (i.e. equal time between each successive cue) creating a precise multilimb tactile metronome;
- **bespoke gait analysis software**, capable of analysing gait data to extract important characteristics and produce reports assessing a person's gait.

The block diagram of the full system's concept is shown in Figure 18.

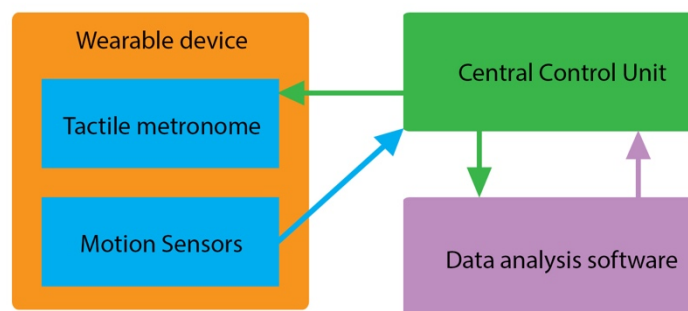


Figure 18 Haptic Bracelet concept. Arrows indicate data flow.

5.2.2 Operation concept

The Central Control Unit (CCU) controls the tactile metronome by sending a “vibrate once now” instruction to the wearable units on alternate legs. Recall that a multilimb approach is used, where each successive tactile cue in the rhythm is delivered to alternating legs.

Each device sends a constant stream of data back from the devices' on-board motion sensors. This data is analysed subsequently to extract gait characteristics, in particular temporal and symmetry values. Having one motion

sensor on each leg allows for ready identification between legs, and a finer grain of data contrasting the details of paretic versus non-paretic steps.

The Haptic Bracelet system conceptual operation is summarised on Figure 19.

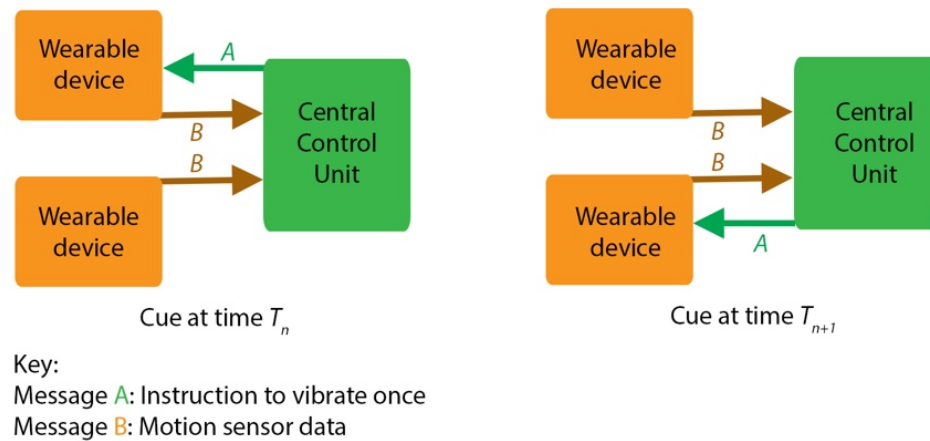


Figure 19 The Haptic Bracelet concept operation. In its default configuration, two wearable units are used – one on each leg. The CCU sends a “vibrate now” instruction message to alternate devices at a predefined rate (period). Both wearable devices send back a constant stream of motion sensor data. Arrows indicate data flow.

5.3 The Haptic Bracelet system implementation

Using an iterative prototype design approach, a number of prototype versions were produced, tested and evaluated, before getting redesigned for the next iteration. Testing was performed in two ways: firstly, gathering empirical data in the lab on the device performance and reliability (with both stroke survivors and able-bodied participants); and secondly, gathering qualitative data from healthcare professionals and stroke survivors on system design. However, instead of describing each system iteration, this chapter focuses on the individual components that make up the Haptic Bracelet system. The iterations of these components are described in the sections below, presenting various technical and design considerations that influenced the development of the system.

The current iteration of the Haptic Bracelets, as illustrated in Figure 20, consists of: two wearable devices; a central control unit; custom built software and firmware for the wearable devices; and analytical software designed and implemented to analyse gait data.

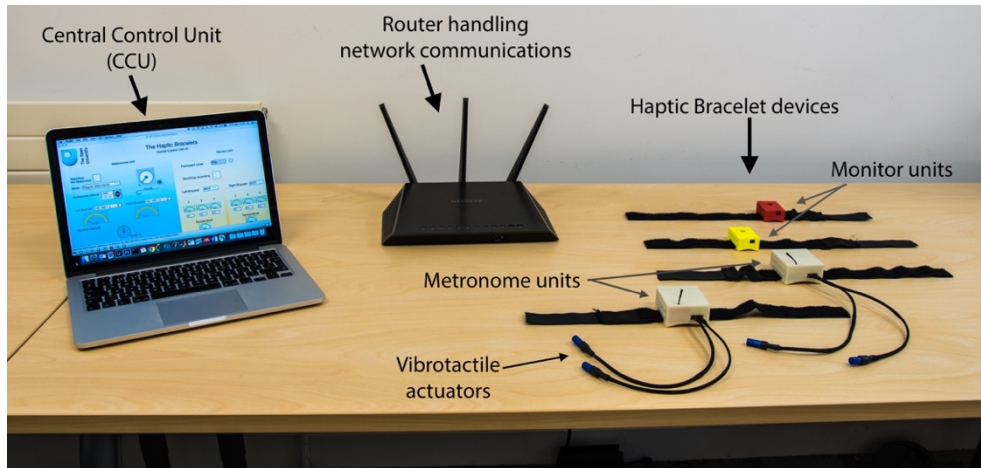


Figure 20 The Haptic Bracelet system consists of two wearable devices, each consisting of a monitoring and a metronome unit, and a central control unit (CCU). A router is used for creating a local network and hosting all communications between the CCU and the wearable devices.

5.3.1 Wearable unit

The wearable units work in pairs (one for each leg). Each unit contains a vibrotactile actuator capable of producing a tactile cue of sufficient, but comfortable intensity to be felt by the user. Each unit also has sensors for recording appropriate motion data (integrated in an *inertia monitoring unit* (IMU) – discussed in detail in the next section on page 83) that can be used for calculating gait characteristics including gait asymmetries and step variability.

Initially both the metronome and monitoring units were designed to exist as one device. However, extensive lab testing exposed one major limitation of this approach. If both the IMU and vibrotactile were connected via a single unit, vibrations from the vibrotactile actuator (see Figure 26, page 91) could travel up the cables and muddy the data.

Therefore, a decision was made to physically separate the tactile metronome and the IMU. Despite this physical separation, both units are controlled via Wi-Fi from a single central control unit, allowing precise synchronisation. Separating the monitor and metronome units also meant that the physical placement of the tactile metronome (optimised for clear perception of the tactile cue) was no longer restricted by the placement of the IMU (potentially optimised for accurate gait data collection). Placement considerations for both the monitoring and tactile metronome unit are described on pages 86 and 96.

Gait monitoring unit

In order to facilitate precise monitoring of motion for gait analysis, an “off-the-shelf” wireless I/O board was used for the gait monitoring unit of the Haptic Bracelet system (see Figure 21). This board, called the x-OSC⁶, was chosen because of its small size, flexibility and nominal high bandwidth.

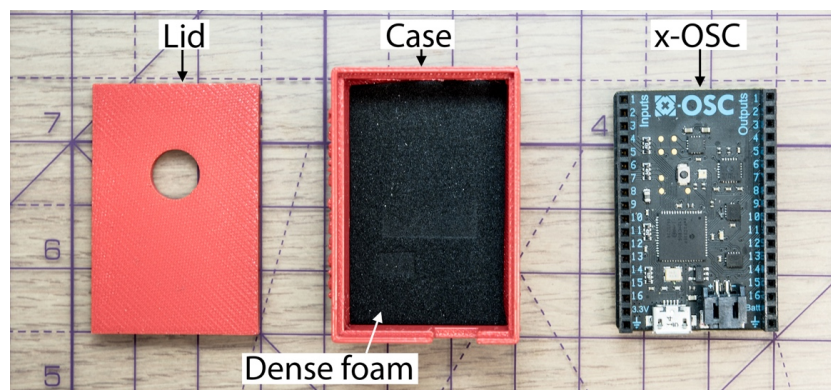


Figure 21 The x-OSC wireless I/O board as used for the gait monitoring unit of the Haptic Bracelet system. A bespoke case was designed and 3D printed for the x-OSC. Dense foam was used to minimise noise in motion data from rattling movement of the x-OSC inside the case.

⁶ x-OSC made by x-io Technologies <http://x-io.co.uk/x-osc> [Accessed: 31/07/2018]

Primarily designed for artists and performance work (e.g. the mi.mu glove⁷) the x-OSC measures at $45 \times 32 \times 10$ mm and is powered by a lightweight Lithium Polymer (LiPo) battery. Monitoring and reacting to motion during artistic performances was one of the primary motivations of the x-OSC production (Madgewick and Mitchell, 2013). It contains a full inertia measurement system (IMU), equipped with an accelerometer, a gyroscope and a magnetometer, each capable of sensing motion in 6 degrees of freedom (x, y and z-axes).

The x-OSC takes readings from these sensors once every 2.5 milliseconds – yielding a sampling rate of 400Hz. This data is sent via Wi-Fi to the central control unit (see Figure 18 for the system's concept design). However, after lab testing it was concluded that operating at the maximum 400Hz sampling rate produced too much data, introducing communication bottlenecks in the system. This caused a high number of packets to be dropped, losing data. The situation was exacerbated when more than one x-OSC was used (as per normal pairwise operation of the Haptic Bracelets).

In order to resolve the problem with lost packets, it proved necessary to establish a reliable sampling rate. (No performance data existed for the version of x-OSC used in this thesis. The sole evaluation in the literature (Madgewick, Harrison and Vaidyanathan, 2011) referred to an early prototype of the x-OSC using Bluetooth rather than Wi-Fi).

Investigation in the lab revealed that a sampling rate of 256Hz (one sample every 3.9 milliseconds) was the highest reliable sampling rate in the context of gait monitoring.

⁷ <http://mimugloves.com/> [Accessed: 31/07/2018]

Consequently, for the gait studies, a 256Hz sampling rate was chosen. This is ample to pick up important gait events with the required accuracy. Results from the sampling rate reliability test are shown below in Table 2. Note that it is difficult to count lost packets reliably; consequently, reliability was assessed in terms of the variability of the mean number of packets received for given nominal sampling rates (Table 2).

Set sampling rate (Hz)	Measured sampling rate (Hz) n=10 measurements
200 Hz	201.31 \pm 0.28
256 Hz	256.96 \pm 0.22
300 Hz	297.64 \pm 4.93
400 Hz	389.34 \pm 7.02

Table 2 The table above shows the sampling rate set on the device versus the actual number of samples received per second. Set at 256Hz produced the closest measured sampling rate with the smallest standard deviation. Higher standard deviation also indicates higher unpredictability on packets lost, hence higher inaccuracies in data.

The accuracy and validation of measurements taken by the Haptic Bracelet's motion capture units in the context of temporal gait characteristics are discussed in section 7.4.3, page 137.

A case was designed and 3D-printed to house and protect the board. The case was designed using SketchUp specifically to be worn around a limb (preferably on the leg near the ankle). A slight curve was implemented to fit the limb for comfort, and slits provided to allow easy securing of the unit with a Velcro strap on the leg. A 3D rendering of the design and photos of the actual 3D printed case are presented in Figure 22 below.

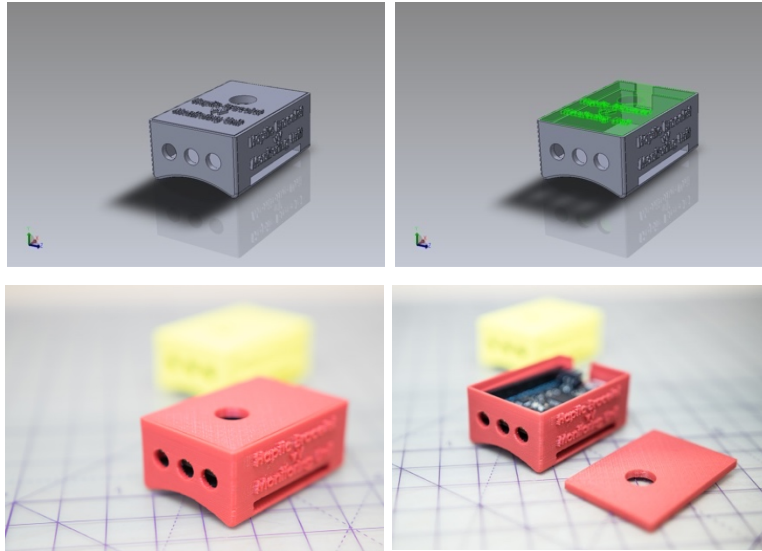


Figure 22 Case used for housing the monitoring unit of the Haptic Bracelet wearable device. The top row presents the 3D rendering of the case used before 3D printing with the finished case in the bottom row.

Placement of the gait monitoring unit

One issue to address as part of the design is *where* on the legs to place the monitoring units. Further investigation of the literature found claims (Evans and Arvind, 2014) that the precise area on the lower limbs where sensors are placed does not appear to have significant performance advantages for measuring gait characteristics. It may be unwise to take this claim as definitive, since Evans and Arvind do not explicitly compare different footwear and different walking surfaces, and it is possible that different footwear/surface combinations might favour different measurement locations. Furthermore, discussions by (Madgwick, 2013), outlined below, suggest that not all measurement locations may facilitate equal accuracy. However, in any case, when designing wearables, measurement accuracy is not the only issue governing placement. The device also has to be: comfortable, safe, unobtrusive when walking and inconspicuous in social settings (Mazilu *et al.*, 2013).

During lab testing, five areas of the lower limbs were considered: the waist, the thigh, near the knee, the ankle, and the top of the foot. The knee area was

excluded from further investigation as this area was reserved for the vibrotactile actuator (placement of the actuator is discussed on page 96 below). Tactile cues from the actuators have the potential of interfering with the motion data, introducing noise that could lower the quality of the captured data. The thigh was also excluded on the grounds of being intrusive for the participant, inconvenient during walk, and too close to the groin area.

The areas considered taken forward to lab testing are shown in Figure 23.



Figure 23 Pictures showing the investigation of possible placements of the Haptic Bracelet's monitoring unit. From left to right: top of the foot, shank of the foot near the ankle, and on the waist. After considering these possibilities, the shank of the foot near the ankle (middle image) was preferred as it appeared to better accuracy and wearability on the walking surfaces used.

Even though placing the devices on the waist could help solve numerous practical problems such as wearability and comfort – people often wear belts – data produced during this setup lacked the granularity needed for this application. When on the waist, gait phases are not as pronounced, making them difficult to analyse. Also, motion data captured from the waist can make it difficult to differentiate between the legs and extract clear temporal information for symmetry analysis.

Evidence from lab testing and documentation from prototype testing of the early x-OSC versions by (Madgwick, 2013), promote the top of the foot as an accurate site for measuring gait events. However, the experiments discussed in (Madgwick, 2013) were designed for testing that author's motion detection

algorithms (Madgwick, Harrison and Vaidyanathan, 2011) and did not consider the wearability and practicalities of wearing such devices. For most people and applications, with current technology, the top of the foot is not practical outside the lab. This location is socially obtrusive and prone to damage. Moreover, adding weight at the top of the foot may introduce safety concerns to hemiparetic users suffering from foot-drop; a condition where, due to physical weakness to the paretic leg, the toes do not lift off the ground high enough during the swing phase. Adding extra weight could worsen this problem, leading to an increase risk of fall and the probability of injury.

After lab testing on placement (see Figure 23) and discussions with hemiparetic patients, stroke survivors, carers and physiotherapists (Chapter 4, page 60), the monitoring units were placed on the shank of the leg (one on each leg) near the ankle. This was considered a comfortable placement that had minimum impact on the way people walk.

One of the advantages of placing the monitoring unit on the ankle is that it is near the location where the heel meets the ground and thus enables the forces that are applied to be measured directly. Furthermore, the ankle is a relatively bony structure (as compared to for example the thigh which has more muscle and fat tissue) and so the impact force is less likely to be absorbed. In addition, the ankle area is at a point of maximum swing when the foot moves forward, therefore, gyroscope data also appear magnified, making detection of stance and swing phases more pronounced.

Tactile metronome unit

The other wearable part of the Haptic Bracelet system is the tactile metronome unit. Unlike the monitoring unit, where an off-the-shelf board was used, the metronome unit was designed and implemented for the purpose of this research. The tactile metronome unit can communicate with the CCU via Wi-Fi, receiving instructions on when to produce a vibration, how strong the

vibration should be and how long the vibration should last (summarised in Figure 33, page 98). Each metronome unit is assigned a unique static IP address during production, and then this address is used by the system and the CCU to identify each device in the network and send all relevant messages. Messages are received by a Wi-Fi board integrated in the printed circuit board (PCB) design. The Wi-Fi board used is an “RN-XV WiFly Module”, programmed to automatically connect to the “Haptic Bracelet network” and be ready to accept messages from the CCU.

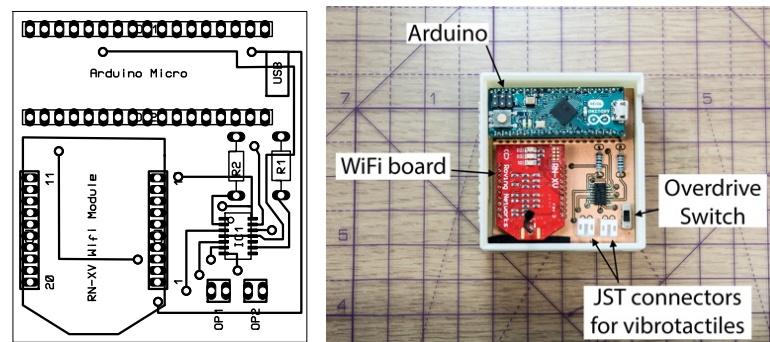


Figure 24 (Left) schematic diagram of Haptic Bracelet metronome unit. (Right) Picture of the implemented device showing the Wi-Fi board; the Arduino controlling the metronome unit; the connectors used for attaching the vibrotactile actuators and an overdrive switch for increasing the vibration intensity - the overdrive function is discussed in page 95.

Messages coming from the CCU are then passed on to an Arduino board. The Arduino board (an Arduino mini – see Figure 24) runs the firmware necessary to interpret the messages from the CCU and sends a signal to the vibrotactile actuators, instructing them to vibrate for a set duration at a set intensity. The decision to have a separate and independent Wi-Fi connection between the CCU and the tactile metronome was made to ensure the network did not bottleneck with information. Earlier iterations where both the monitoring unit and the tactile metronome unit used the same Wi-Fi connection experienced high packet drop rates, making both the sensor readings and haptic metronome appear jittery and unstable. Separating the two streams of data solved this problem.

Between the Arduino and the vibrotactile controller, another piece of electronic circuit is designed and implemented allowing the use of a technique known as “active braking”. With active braking the motor inside the vibrotactile responsible for generating the buzzing sensation of the tactile cue is abruptly stopped, generating a “sharper” cue sensation. The process of active braking and the way vibrotactiles operate will be described in more detail in the next section below.

The PCB and all electronics are housed in a 3D printed case, designed to fit everything for protection and wearability (see Figure 25 below). As with the monitoring unit, the case of the metronome unit is also designed with a curve to fit comfortably on the wearer’s leg and a slit for the Velcro straps to pass through for securing the device.

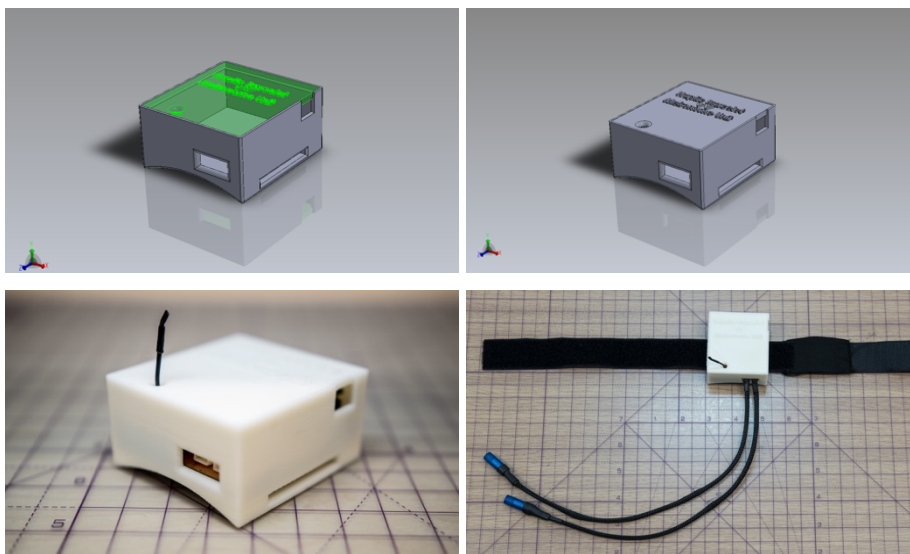


Figure 25 Case used for housing the metronome unit of the Haptic Bracelet wearable device. Top row presents the 3D rendering of the case used before 3D printing with the finished case in the bottom row.

Vibrotactile actuator

The tactile cues making up the haptic metronome are produced via a pair of vibrotactile actuators. These actuators are a pair of strong vibration motors,

made by Precision Microdrives Limited⁸ capable of delivering “sharp” tactile cues with relatively low latency (see Figure 26). As this is a prototype system, two actuators are used per device mainly for maximum placement flexibility. Each actuator was attached to a 30 cm cable and attached to the device via a JST connector. Braided cable sleeves were used for allowing the cables to be flexible and soft when worn on the leg but strong enough to withstand testing (see Figure 26).

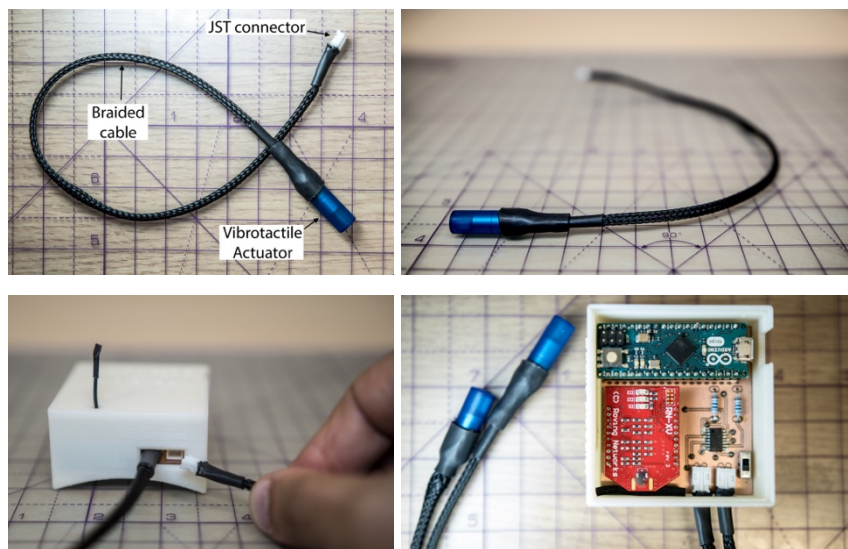


Figure 26 The Vibrotactile actuator used for producing the tactile cues. Braided cable housing was used for keeping the wires flexible and soft when worn on the leg but strong enough to withstand testing. A standard JST connection was used for attaching the actuator assembly on the metronome unit.

The manufacturer’s specification sheet states that it takes 36 milliseconds for the motor to reach its maximum operation (see Appendix 4 on page 192 for the actuator's data sheet). However, the time it needs to be felt by a given person may vary depending on characteristics such as the sensitivity of the person. Still, crucially, any latencies in given circumstances should be constant and

⁸ Precision Microdrives Limited website: <https://www.precisionmicrodrives.com> [Accessed 31/07/2018]

consequently should not affect the perception of a steady haptic metronome (see Figure 27 for an example).

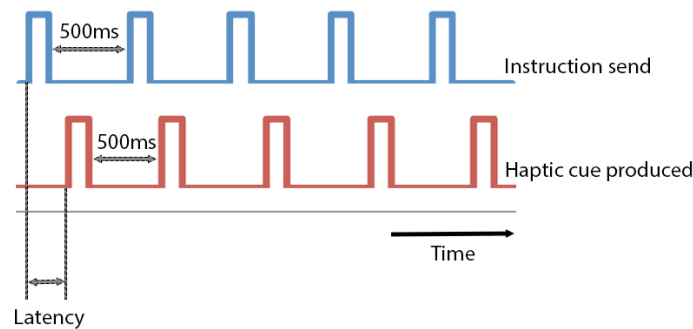


Figure 27 If there is a constant latency of 36 milliseconds, for example, each cue in a metronome with a period of 500 ms, will still arrive on time - once every 500ms).

Controlling the vibration intensity

The intensity of the vibrotactile actuator was regulated using a technique known as *Pulse Width Modulation (PWM)*. This is a standard and widely used technique of obtaining an analogue signal from a digital one. Effectively, this technique allows precise digital control of a voltage from zero up to the maximum to be delivered to the vibrotactiles. The frequency of the vibration (i.e. how fast the motor inside the vibrotactile actuator spins) increases with the voltage supplied to it in a logarithmic relationship. However, the frequency value is unlikely to play a dominant role in the perception of the cues for the following reasons, which relate to haptic perception and skin physiology.

The default placement of the haptic bracelet metronome unit, as discussed in page 96 below, is on the leg near the knee. This area is covered in what is termed “hairy skin”, which is low in concentration of the particular mechanoreceptors (sensory neurons) responsible for perceiving *vibrational* stimuli – namely Pacinian and Meissner's corpuscles. Hairy skin does, however, contain Merkel's disk and Ruffini endings which can detect *pressure* and *skin stretch* (Kandel, Schwartz and Jessell, 2012). Generally, tactile cues

coming from the vibrotactile actuators are perceived more as a “tap” sensation than as a vibration, as reported by several participants in pilot testing (Chapter 4). This suggests that the dominant mode of perception will not be vibrational.

During the studies in this research, when choosing the intensity of cues, an informal qualitative approach was preferred, ensuring firstly that the participants could feel the cues, and then adjusting the intensity to personal preference.

Although, for reasons outlined above, frequency issues are unlikely to play a dominant role in perception of the cues, nevertheless they may play some role in the perception of perceived intensity. Consequently, the relation of applied voltage to resulting frequency was briefly investigated. The manufacturers of the vibrotactile actuator provide a datasheet showing the relationship between voltage and frequency; however, to be on the safe side, as the Haptic Bracelets use a different circuit design than the one measured by the manufacturers, the intensity of the vibration output was measured empirically in the lab.

To measure intensity, the vibration actuator was first clamped on a rigid structure and the vibration produced was recorded at different vibration intensity levels (i.e. different voltage levels) using a Zoom H1 digital voice recorder. The recorder was secured on an isolated microphone boom arm to avoid any mechanical vibrations interfering with the audio recording (see Figure 28).



Figure 28 Setup used for measuring the vibration intensity of the Haptic Bracelet's metronome unit.

In this test, the vibrotactile actuator was set to produce ten consecutive tactile cues (vibrations) 1000 ms apart, with each lasting for 200ms. This test was repeated for a range of voltage values. Figure 29 illustrates two haptic cues at maximum voltage during frequency analysis in Adobe Audition CS6.

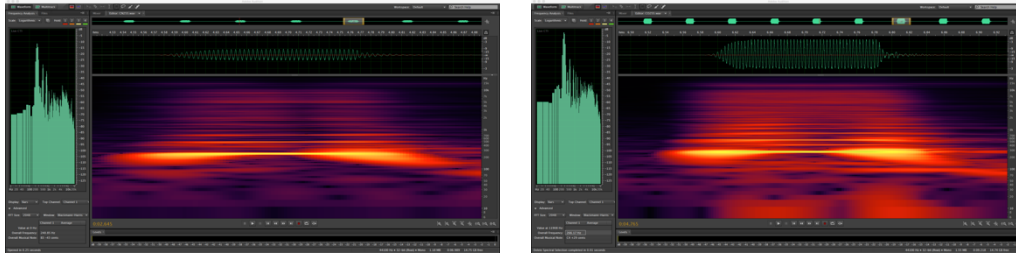


Figure 29 Vibration frequency analysis performed in Adobe Audition CS6. In this figure one tactile cue is shown at maximum intensity (maximum voltage) with and without overdrive (left and right respectively). The audio signal is analysed, producing the frequency of vibration. The overdrive function is discussed in page 95.

From the empirical measurements, the findings indicate that as the voltage value increases, the vibration frequency also increases (motor spins faster) in what appears to be a logarithmic relationship (see Figure 30). These results agree with the manufacturer's results⁹.

⁹ Data sheet available from: <https://goo.gl/HtVFQR> [Accessed: 31/07/2018]

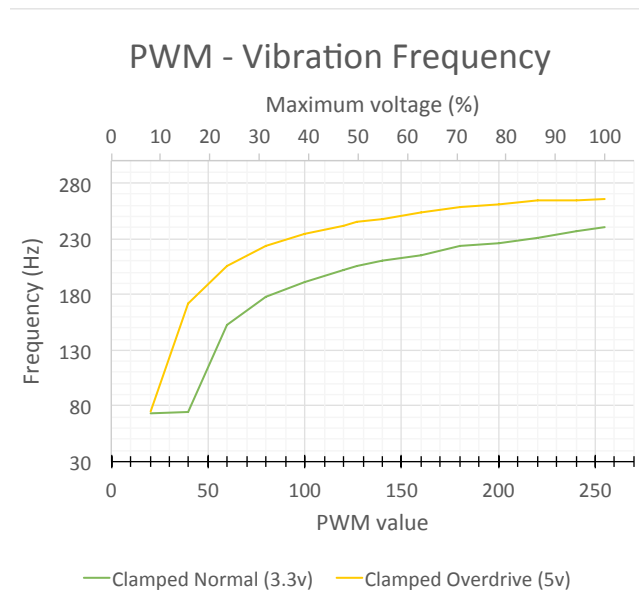


Figure 30 Results from empirical testing investigating the relationship between PWM values (effectively voltage) and changes in vibration frequency of the vibrotactiles used in the Haptic Bracelet system. The yellow line indicates results of overdrive mode operation.

Qualitative information from lab tests and pilot runs suggest that, as might be expected, the perceived intensity increases as voltage increases. Ideally, a psychophysics experiment should be carried out to further understand how the perceived intensity of the vibration changes in relation to the actual intensity (characterised by the frequency and voltage).

To further enhance the way haptic cues are felt, a mechanical brake was implemented. The brake works by mechanically stopping the motor rotating instead of waiting for it to decelerate to a natural stop, thus giving a sharper pulse. This brake action was implemented in the firmware at the end of each tactile cue. During lab testing it was found to make the cue feel, as one pilot participant described “snappier”, or “sharper”.

In addition, a mechanical “overdrive switch” was implemented on the PCB of the tactile metronome unit, allowing for an increased intensity of the tactile cue. The motivation of implementing the brake and overdrive functionality was comments from one participant in the observation study (section 4.2, page 60).

That participant was suffering from extreme sensory deficits (75% loss of tactile sense on lower limbs), a common condition with stroke survivors and hemiparetic patients. Providing a tactile cue of boosted intensity allowed participants suffering from sensory deficits to be accommodated who would otherwise not be able to feel the rhythmic haptic cue. This switch can be seen on Figure 24, page 89.

Since the voltage supplied by this overdrive switch was over the manufacturer's recommended levels, it was only sparsely used on certain cases of participants suffering from extreme sensory deficits. No safety issue was raised since the voltage was still small (5V) and the motor is enclosed within a thick waterproof and shatterproof layer of plastic. The way the overdrive switch affects the vibration frequency is shown on Figure 30 (yellow line).

Placement of tactile metronome unit

Considering the basis of entrainment as discussed on page 12, in principle *any* location of the haptic rhythm source could be used to establish entrained motor movement. However, having the haptic rhythm originating on the legs may have other potential benefits: for example, helping hemiparetic users to *direct their attention*, producing a clear spatial mapping, linking the rhythm's buzzes to actions and differentiating which buzz corresponds to which leg.

Discussions with physiotherapists suggested a second potential benefit: cueing individual limbs can help focus kinesthetic and *proprioceptive capabilities*, helping to identify where each limb is in space in relation to the rest of the body; an ability often lost from hemiparetic patients.

For these reasons, it was preferred to place the haptic metronome unit on the shank of the leg (one on each leg) just below the knee. The vibrotactiles (parts of the device that vibrate, see Figure 26 above) could then be strapped with another Velcro strap near the skin, as shown on Figure 31. Physiotherapists advised placing the vibrotactile on the outside of the knee, on the upper part of

the tibialis anterior muscle, as it is a relatively bony structure which helps to amplify tactile cues (not much fat or muscle tissue to absorb the cue). Additionally, major nerves pass through that area, increasing the chance of the tactile cues being felt even by patients with sensory deficits.

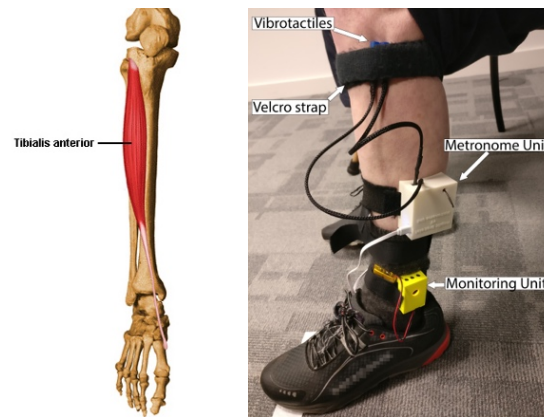


Figure 31 Placement of the vibrotactile actuator on the patient's body. The actuator is secured using Velcro straps on the upper part of the leg's shank near the knee on the top of the "tibialis anterior" muscle.

However, this placement advice may have been influenced by the muscle facilitation technique physiotherapists use during the acute stages of gait rehabilitation after stroke. As described on page 51, physiotherapists often massage that muscle during physiotherapy sessions to help promote (facilitate) movement.

Special considerations for placement

Some people affected by hemiparesis wear splints and other orthotic devices to help maintain the correct position of their lower foot while walking. In addition to orthotics, patients may suffer from other conditions linked to stroke and the medication they receive, causing their legs to swell (see Figure 32 below for an example). Attaching the devices on flexible Velcro straps made it possible to secure the devices on the patient's legs in a safe and comfortable manner regardless of their leg's circumference.

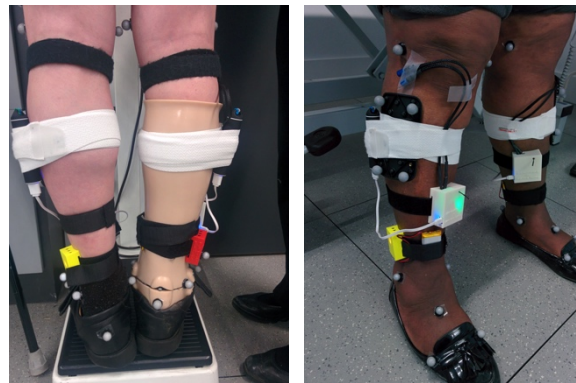


Figure 32 Left: Participant wearing an orthotic splint on his paretic (right) foot. Right: Participant with swollen feet; a common side effect linked to stroke medication.

5.3.2 Central control unit

The central control unit (CCU) is responsible for synchronising the two wearable units and controlling the haptic metronome's periodicity by sending a “vibrate now” instruction to the wearable units on alternate legs. The CCU also controls the vibration intensity and the vibration duration (summarised in Figure 33 below).

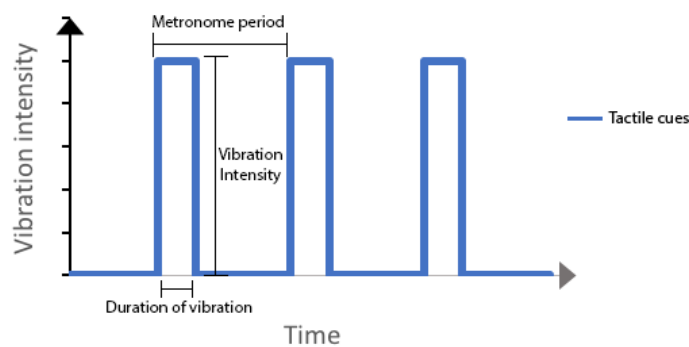


Figure 33 Graphic representation of the aspects of the vibration the CCU controls. These include the metronome period, the vibration intensity and the vibration duration.

Data arriving from the wearable units is timestamped by the CCU to ensure consistent timing (timestamps based on the same clock) before storing for later analysis by the data analysis software.

The Central Control Unit (CCU) had two primary aims:

- handle data coming *in* from the on-board sensors of both monitoring devices;
- handle messages going *out* to both tactile metronome units.

The user interface of the CCU (implemented in Max 6¹⁰) is presented in Figure 34.

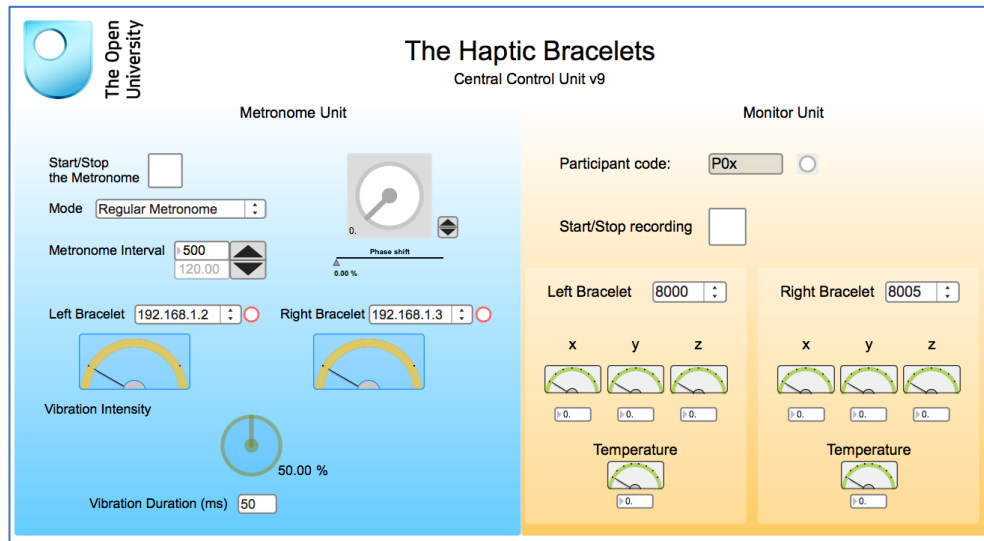


Figure 34 The Central Control Unit's (CCU) user interface (UI). The left side contains the controls for the metronome unit. These controls include the intensity of tactile cues, the duration, and the period between successive cues. The right side contains the controls to start and stop recording motion data. The CCU was implemented in Max 6¹⁰.

As seen in Figure 34 above, the Max patch controlling the CCU is split into two components; the Metronome and the Monitor unit. The Metronome unit (left in figure above) functionalities are straight forward. There is a button to start and stop the metronome, a number field to set the period of the haptic metronome in milliseconds, a drop-down field to select the two devices (identified using their IP addresses), a circular slider to adjust the vibration

¹⁰ Max website: <https://cycling74.com/products/max> [Accessed 31/07/2018]

intensity and lastly a field to define the vibration duration in milliseconds. For each cue, a message is sent containing the value for the vibration intensity and duration at the predefined period, alternating between the two IPs. The Haptic Bracelet wearable unit reads and interprets the message, producing the necessary vibration and hence the tactile cue.

The “Monitor unit” of the CCU patch (right in figure above) listens to two ports in the network; one for each of the two wearable units. As explained in section 5.3.1 (page 82), the monitor unit is made of a x-OSC, an “off-the-shelf” board run on pre-compiled firmware. This meant any limitations introduced by the restrictions of the pre-compiled (hence un-customisable) firmware of the x-OSC had to be dealt within the CCU software.

The x-OSC is designed to send a constant stream of OSC messages containing IMU data from all of its on-board sensors (including voltage level and temperature sensors) while it is powered on. Logging everything would create unnecessarily big and “noisy” files making them difficult to process and extract any meaningful information efficiently. Therefore, the “Monitor” section of the user interface (UI) contains a start/stop control allowing for the recording of data during a period of relevance where the most meaningful gait related information can be extracted (e.g. during the 10 meter walks in the study described in Chapter 7, page 121).

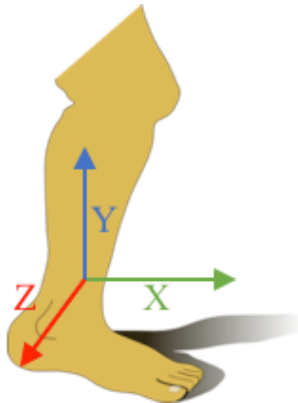
Recording data from all three axes (x, y and z) of the IMU’s accelerometer and gyroscope are collected, structured (i.e. placed in a predefined order), timestamped by the CCU and stored for later analysis. The time in milliseconds since the start of the recording session is used for the timestamp.

Data files are finalised and saved (one for each monitor device/leg) when recording stops. These files can then be passed on to the data analysis software for extracting gait related characteristics and information.

5.3.3 Data analysis software

Software was designed and implemented for analysing the data coming in from the wearable units. Various kinds of temporal information are analysed including step times and duration of the gait cycle phases (i.e. stance and swing). Values used for characterising gait – such as the overall gait asymmetry ratio (see page 24) can then be calculated, producing reports summarising the results.

As discussed in Chapter 2, temporal information is vital for characterising gait. Important temporal gait characteristics include: step time, swing time and stance time. From these characteristics, the overall gait asymmetry (a standardised value for characterising gait) can be calculated. A bespoke script was developed in Matlab that takes as input the two log files (one from each leg) and outputs a report containing the most common gait related values used to characterise gait.



Step times are calculated based on the accelerometer data. During walk, the leg moves in all directions; up and down along the Y-axis, forwards along the X-axis and even side to side along the Z-axis (Figure 35). Therefore, the magnitude of the resulting force vector (RFV) can be calculated using equation (8) below:

Figure 35 Directions where legs move during walk.

$$RFV = \sqrt{x_i^2 + y_i^2 + z_i^2} \quad (8)$$

This equation gives the resulting vector force, considering all three axes of motion; the direction of motion is the direction the foot moves in space. The

exact direction is not important in this case, as the only important value is when the leg strikes the ground.

When the foot strikes the ground, a peak is expected, caused by the acceleration of the foot towards the ground followed by a sudden deceleration on impact. The script developed for analysing these data contains an algorithm based around Matlab's FindPeaks() function where peaks in the data are identified (see Figure 36).

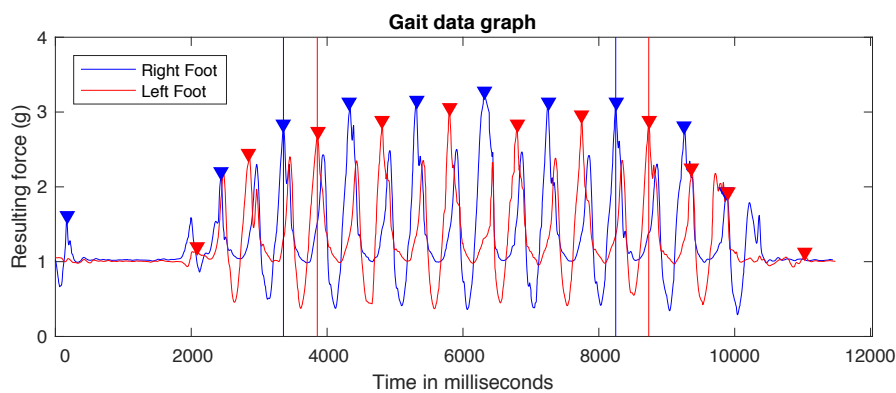


Figure 36 Output of the bespoke gait analysis Matlab script. The blue graph represents data from the right foot and the red graph from the left. Triangles on top of peaks indicates the moment each foot hits the ground. This data is used for calculating several pieces of temporal information such as step and stride times. Vertical solid lines indicate the analysis window. Anything outside this window is not included in the analysis. This window was implemented to avoid noise from movement before and after the walk causing spurious readings and was manually adjusted for every trial.

In the next stage, the precise time in milliseconds between each peak of the same leg (cycle time) and alternating legs (step times) is calculated. Gyroscope readings are also used to determine whether the foot is stationary or if it is swinging forward, making it possible to determine stance and swing phases (see Figure 4 – page 18 for information on gait phases).

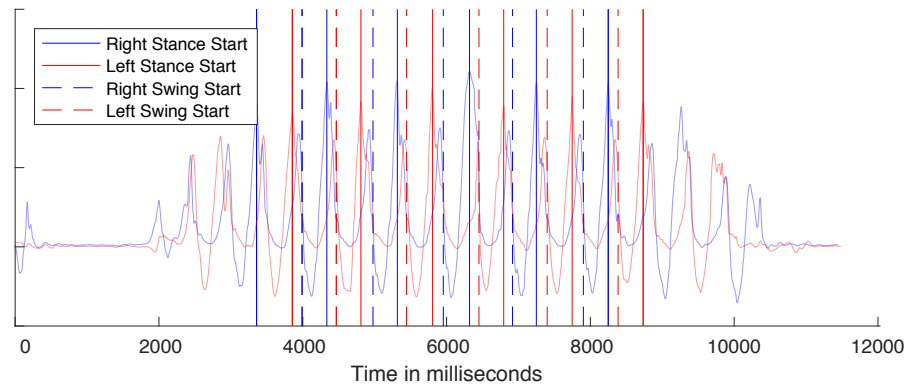


Figure 37 This graph shows part of the report produced by the gait analysis script. It is using the same colour scheme and analysis window as the graph in Figure 36 above. Data from this graph is used for detecting and calculating stance and swing phases. Solid lines indicate the start of a stance phase and dotted lines the start of a swing phase.

A report is then produced containing all this information in a way that can be explained to a non-technical physiotherapist or the patient. A sample of this report can be seen in Appendix 3, page 189.

The overall temporal asymmetry (OTA) value can then be calculated using Equation (6) as described in page 26 after data from a series of walks are gathered.

5.4 Chapter summary

Given that the aim of this thesis is to explore a novel approach to gait rehabilitation, a prototype haptic cueing and monitoring system was iteratively designed, implemented and tested, informed by formative feedback and on-going in-lab tests. This system informed the design of a special purpose prototype used for the study in Chapter 6 and was the vehicle for the studies reported in Chapter 7.

The prototype system, called the Haptic Bracelets, took inspiration from a pre-existing wearable system designed primarily for musical purposes. The new Haptic Bracelet system, like its predecessor, consists of a set of wearable

devices designed to function as a multi-limb haptic metronome, delivering successive tactile cues to different limbs.

One early design decision for the new prototype was to physically separate the haptic cueing and motion sensor functions for each limb into two separate physical units. There were three reasons for this separation. Firstly, on-going testing in the lab revealed that having these functions in the same unit could muddy the sensor data, due to the sensors picking up the vibrotactiles. Secondly, having both functions controlled by a single processor restricted the bandwidth of the sensor data, also causing occasional metronome jitter. Finally, splitting the device into two units enabled their respective placements on the leg to be optimised for function and comfort, as further discussed below.

To implement the monitoring unit, an off-the-shelf sensor was housed in a custom-designed casing. Bespoke software was written to record and analyse various temporal characteristic including step time, stance time, swing time, and derivative values such as overall temporal asymmetry.

Formative studies demonstrated that some hemiparetic users had relatively severe sensory deficits that made it hard for them to feel the vibrotactiles - even at their maximum intensity. Consequently, an overdrive mechanism for the cueing unit was designed and implemented to resolve this problem.

Decisions about where, on participants' legs, to locate the metronome versus the monitoring units were influenced by the formative studies and in-lab testing respectively - as now detailed.

Formative studies with health professionals influenced decisions about the positioning of the cueing units: these were placed near the tibialis anterior muscles near the knee (see Figure 31, page 97). This allowed for optimal sensing of the cues, particularly for users with high sensory loss, while minimising interference with limb movement.

By contrast, based on feedback from on-going lab testing, the monitoring units were located at the lower shank of the leg, near the ankle, where clarity of impact and swing force data was optimised.

Chapter 6

Study 1: Haptic rhythm perception - The haptic tap test

The study presented in this chapter was aimed primarily at investigating whether sensorimotor response, in the form of finger tapping, is feasible for haptic rhythms in a similar way as it is for audio and visual rhythms.

People can generally synchronise their actions to the sound of a regular beat, provided it is not too fast or too slow, as evidenced by diverse tapping experiments (Repp, 2005). These experiments have empirically established fairly consistent upper and lower bounds on humanly possible synchronisation tempi. For reasons outlined below, these limits generally do not seem to reflect limitations on motor ability, but rather perceptual or cognitive limits. However, the existing empirical evidence relates almost exclusively to synchronisation to auditory and visual stimuli. Corresponding upper and lower limits for haptic stimuli do not appear to have been established. Since the present work is predicated on human abilities to synchronise to regular haptic beats, it was decided to investigate the workable range empirically. Although the present research is intended specifically to help those with physical cognitive and perceptual limitations, these conditions tend to vary idiosyncratically. Consequently, to investigate human haptic synchronisation ability and the entailed limitations generally, it was decided to work with healthy, able bodied participants.

The results of this investigation along with insights gained on sensorimotor synchronisation via entrainment to haptic rhythms was then carried forward in the next study – described in Chapter 7 –, where brain injury survivors were asked to walk following a haptic rhythm, with the rhythm's period set to match their own natural walking pace.

A shorter version of the procedure described in this chapter was subsequently used in the study discussed in Chapter 7 as a screening test for hemiparetic participants. The *haptic tap test*, as it was later called, gave an empirical indication of the participants' cognitive and perceptual ability to entrain to a rhythm for walking.

6.1 Background

Previous research (Repp, 2006b) has identified upper and lower bounds on the tempi within which sensorimotor synchronisation to audio and visual rhythms is possible.

Two different, but equally valid ways of quantifying these limits are in terms of *tempi* and *inter-onset-intervals* respectively. The inter-onset interval (IOI) of an isochronous (regular) rhythm is the *period* between successive beats. Note that when a tempo is fast, the IOI is low, and vice versa.

The lower IOI limit (fastest tempo) for reliable tapping to audio and visual rhythms occurs where rapid regular beats are too fast for reliable synchronisation 50% of the time, and the tapping phase and tempo starts to drift (Repp, 2003). The upper IOI limit (slowest tempo) occurs where successive cues are perceived as individual, unrelated events.

Interestingly, the lower limits (but effectively not the upper limits) are different for auditory and visual stimuli. In tapping experiments with isochronous rhythms, the lower IOI for audio was found to be 123 ms, whereas for visual

rhythms it is 459 ms (Repp, 2006b). The upper IOI limit, on the other hand, is similar for auditory and visual sequences at around 1300 ms.

By contrast, no clearly defined sensorimotor limits have been established for the haptic sense.

6.2 Haptic rhythm perception

The purpose of this study was to identify a usable tempo range at which healthy, able bodied participants can tap along to regular rhythm cued haptically by vibrotactiles. Measures were taken to avoid participants hearing the sound of the vibrotactiles, as detailed below. Healthy participants were instructed to tap the index finger of their dominant hand in synchrony with a vibrotactile rhythmic cue delivered to the other hand. A range of tempi were used.

6.2.1 Participants

Twenty participants (fourteen males, two left handed, mean age 32.55 ± 6.77) gave written informed consent to take part in the study. All participants reported themselves free of any neurological disease, head trauma, or musculoskeletal impairment that would influence their haptic sense or tapping ability.

6.2.2 Materials and data collection

Before testing started, participants were asked to sit in front of a table and make themselves comfortable. At this point the procedure was explained in detail and participants were asked if they had any questions. They were then helped to strap a vibrotactile device (see Figure 39) on the wrist of their non-dominant hand, near where the radius and the carpal bones join. The vibrotactile device was strapped on the wrist using two Velcro straps and remained there for the duration of the study. The vibrotactile device was a specially adapted, wired version of the Haptic Bracelet's metronome unit

(discussed in Chapter 5). Figure 38 shows the wired Haptic Bracelet prototype used in this study.

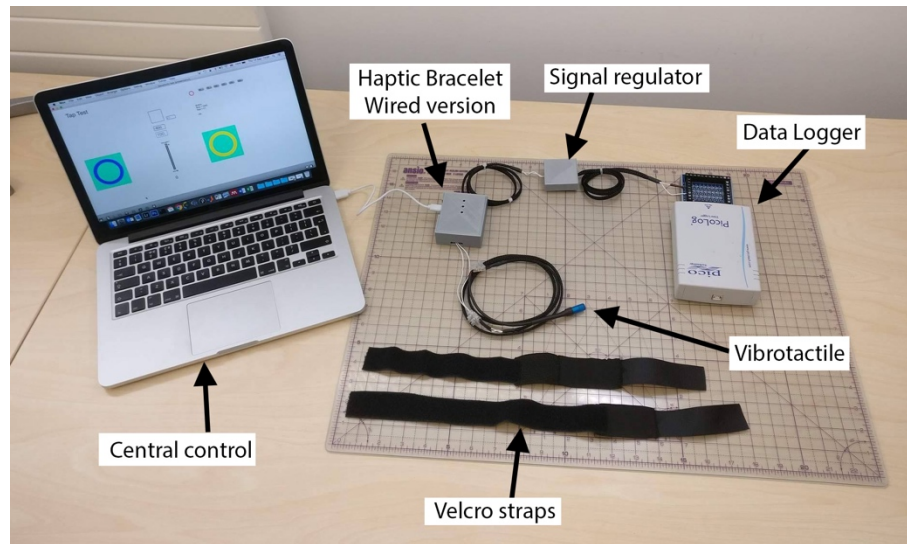


Figure 38 Wired Haptic Bracelet prototype used for the rhythm haptic perception study. A laptop acts as the central control, regulating the period of the haptic rhythm. The wired version of the haptic bracelet is controlling the haptic cue delivered through a vibrotactile actuator. Each cue is also logged via a connected data logger. The signal regulator shown in this figure is used for stepping down the voltage of the cue and protecting the logger's sensitive electronics.

The wired version of the metronome unit minimises communication delays thus enabling millisecond accuracy in recording the precise time of each tactile cue via a directly connected data logger.

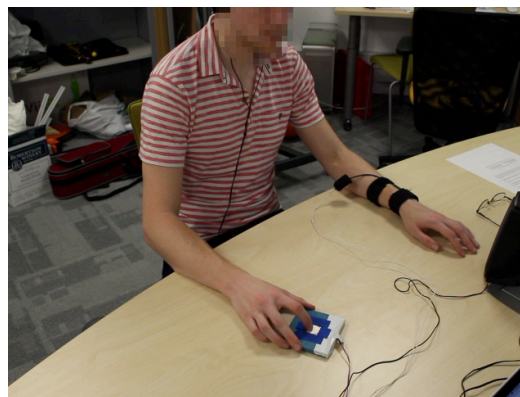


Figure 39 Participant tapping the button with his right index finger. The vibrotactile of the Haptic Bracelet device is secured on his left wrist using a pair of Velcro straps.

The precise timings of the taps were registered when participants tapped onto a piezoelectric sensor mounted in a custom designed, 3D printed enclosure (see Figure 40). The signals from the piezoelectric sensor and the Haptic Bracelet were recorded as time stamped analogue voltage readings via a PicoLog1012 data logger, operating at a sampling rate of 1kHz (one sample every millisecond).

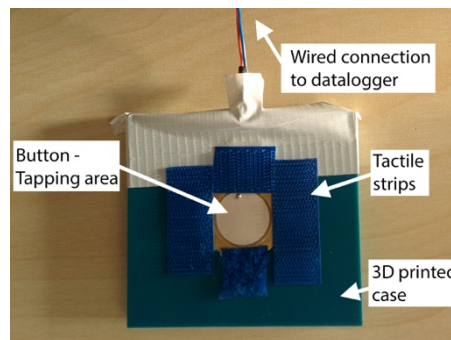


Figure 40 Piezoelectric sensor acting as a button fixed in 3D printed case. Participants were asked to tap on the button while keeping their eyes closed, so tactile strips were used help to guide the participant's finger to the button by sense of touch.

Given that no synchronisation limits for synchronisation by sense of touch had previously been established, the periods for this study were chosen from within the audio and visual limits mentioned above. Consequently, periods chosen for the study were 300, 500, 600, 700, 900 and 1100 ms. The reason for choosing 300 ms as the lowest IOI is that it is halfway between the lower IOI limits for auditory and visual of 123ms and 459ms respectively. The intermediate IOI period of 600 ms was included as it is widely considered to be the preferred natural human tempo for finger-tapping (Delevoye-Turrell, Dione and Agneray, 2014).

6.2.3 Procedure

Each participant completed three sets of six trials. The six trials corresponded to stimuli at the six different tempi. In any given set of trials, the six tempi were presented in a different random order for each participant. Each trial lasted for 30 seconds, and individual vibrotactile cues had a duration of 100ms.

Pink noise was played through a pair of external loudspeakers during the entire testing period, to mask any external background noise and the slight audible “buzz” from the Haptic Bracelet. Pink noise¹¹ was used on the grounds that it has equal energy per octave, and, since human perception is generally logarithmic, this appears to match better than white noise to the following two goals, taking into account the way in which human perception is organised (Gescheider, 1997):

- masking noise uniformly (from a perceptual point of view) across the human frequency range;
- maximising comfort.

Indeed, participants during the pilot study reported pink noise to be more comfortable to hear over long periods of time than white noise.

Participants were asked to keep their eyes closed during trials to minimise visual interference. The choice of having the eyes closed rather than the use of a blindfold was motivated by participant reports of discomfort and claustrophobia with a blindfold during the pilot study.

Participants were also asked to minimise any movement other than tapping (i.e. not to tap their feet or nod their head to the rhythm) during the trials so as not to complicate their focus on the external stimuli.

6.3 Results

The sampled data from the data logger were processed to extract the time of each finger tap and haptic cue onset. Event onsets (haptic cues and taps) were identified as local peaks in the data, which were extracted using a Matlab

¹¹ Pink noise used: <https://www.youtube.com/watch?v=ZXtimhT-ff4> [Accessed 31/07/2018]

script. An adapted version of MatTAP (Elliott, Welchman and Wing, 2009) – a free suite of tools designed and developed for analysing responses in finger tapping experiments - was then used for aligning target and tap events, detecting any taps omitted by the participant.

6.3.1 Outlier exclusion criteria

All data were examined for outliers. Outlier values were identified using the Tukey's fences method (Sullivan and LaMorte, 2016). Using this method, the interquartile range of the data had to be calculated. This involves dividing the data recursively into four parts as follows. Firstly, the data is split into two parts by taking the median of the data as a whole. Then the median of each of the two parts is taken, yielding four parts. The three median points are referred to as "quartiles". Perhaps confusingly, there are four parts to the data, but only three quartiles needed to separate them.

The lowest value median is referred to as the first quartile (Q1), the next highest value median is the second quartile (Q2) and the highest is Q3. The distance spanned by the middle two of the four sections, obtained by subtracting Q1 from Q3 (Q3-Q1), is known as the "interquartile range".

Tukey's fence method defines outliers as any values lying at a distance greater than 1.5 times the interquartile range beyond Q3 and Q1 respectively. The equations used are:

$$\text{Lower outlier limit} = Q1 - (1.5*(Q3 - Q1)) \quad (9)$$

$$\text{Upper outlier limit} = Q3 + (1.5*(Q3 - Q1)) \quad (10)$$

Two of the twenty participants had two or more outlier values in the 600 ms metronome condition (which, as previously noted is considered the default human unforced tempo in finger-tapping paradigms) and were excluded from the study. Outlier values for the remaining participants are reported in each part of the analysis.

6.3 Results

6.3.2 Data analysis

Using exclusion criteria mentioned above, 34 of the 324 IOI values (18 participants x 6 conditions x 3 trials) were removed from the data as outliers. The remaining data are shown in Figure 41.

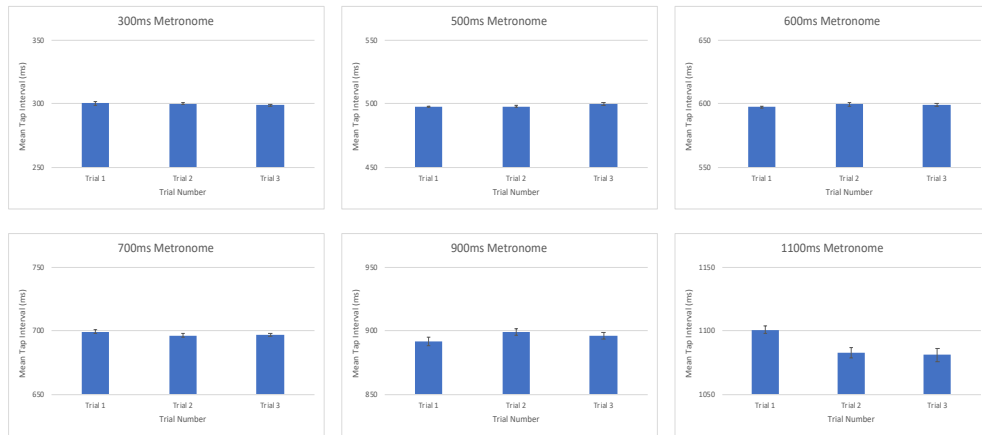


Figure 41 Shows the mean tap intervals produced for the different target periods for all participants. Note that the y-axes for the different metronomes start at different values but are set to the same scale. The error bars show one standard error of the mean.

Data were analysed within-subjects, investigating the ability of participants to tap in synchrony to haptic rhythms of different tempi. Specifically, the data were analysed using a repeated measures ANOVA with the following two within-subjects' factors:

- metronome interval (300, 500, 600, 700, 900, 1100 ms); and
- trials (1,2,3).

Unsurprisingly, the mean time intervals between taps were significantly different from across the mean interval conditions ($F(5, 25) = 24191.857$, $p < 0.001$) indicating the target metronome was indeed influencing the tapping tempi. The trial order did not significantly influence the participants' tapping ability ($F(2, 10) = 0.153$, $p = 0.860$), indicating that the trial sequence had no effect on the tapping ability, and therefore, no learning effects were observed.

There was no significant interaction between trial order and the mean interval conditions ($F(10, 50) = 1.574, p = 0.142$).

Paired-samples t-tests were also conducted to compare the mean tap intervals in different trials of the same metronome interval. i.e. – For every target metronome interval (300, 500, 600, 700, 900, 1100 ms) the following comparisons were made: Trial₁ vs Trial₂, Trial₁ vs Trial₃, and Trial₂ vs Trial₃.

With 18 comparisons, the Bonferroni corrected alpha for the t-tests was 0.003 ($\alpha = 0.05/18$). For most trials (16/18) there was no significant difference between the intervals produced by the participants in different trials. However, for the 1100 ms metronome interval, the participants tapped significantly faster on their second ($t(14)=2.496, p=0.026$) and third ($t(14)=2.998, p=0.010$) trials than on the first trial. Participants also tapped faster on the first trial of the 900 ms metronome interval than they did on their second and third trials, without reaching statistical significance ($t(14)=-2.027, p=0.062$).

Coefficient of variation of tap intervals

While the participants could, on average, synchronise with the haptic cues across every target tempo, there were some differences across conditions in the variability of the mean tapping tempi. To test for this variability, the coefficient of variation (CV) was calculated for every trial mean. The CV was calculated by dividing the standard deviation of the intervals by the mean tapped interval ($CV = \sigma/\mu$), giving a normalised characterisation of this variability. Low variance, and thus low CV, would be expected when participants demonstrate a high level of consistency in the timing of their taps. As with the mean tap intervals, outliers were removed from the CV data. The trimmed data are shown in Figure 42.

6.3 Results

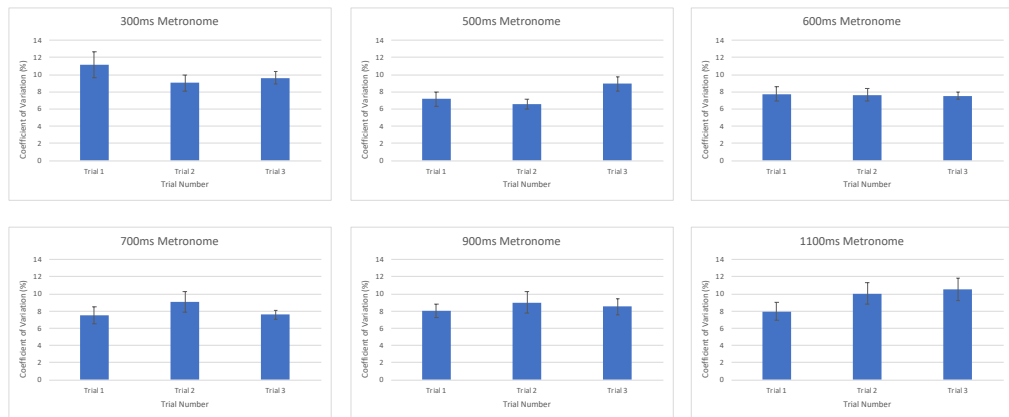


Figure 42 The coefficient of variation of the intervals between taps for the different target IOI period values. One standard error of the mean is shown.

As before, the data were analysed using a repeated measures ANOVA with the within-subjects' factors of target IOI period (300, 500, 600, 700, 900, 1100 ms) and trials (1, 2, 3). The CV of the tap intervals did not vary significantly between trials ($F(2,10)=0.78$, $p=0.926$) or with the intervals of the target IOI ($F(5,25)=13.373$, $p=0.229$). There was no interaction between the two factors ($F(10,50)=8.770$, $p=0.449$), indicating that the trial order did not influence the change in CV, and therefore there was no learning effect. The CV data, averaged over trials, are shown in Figure 43.

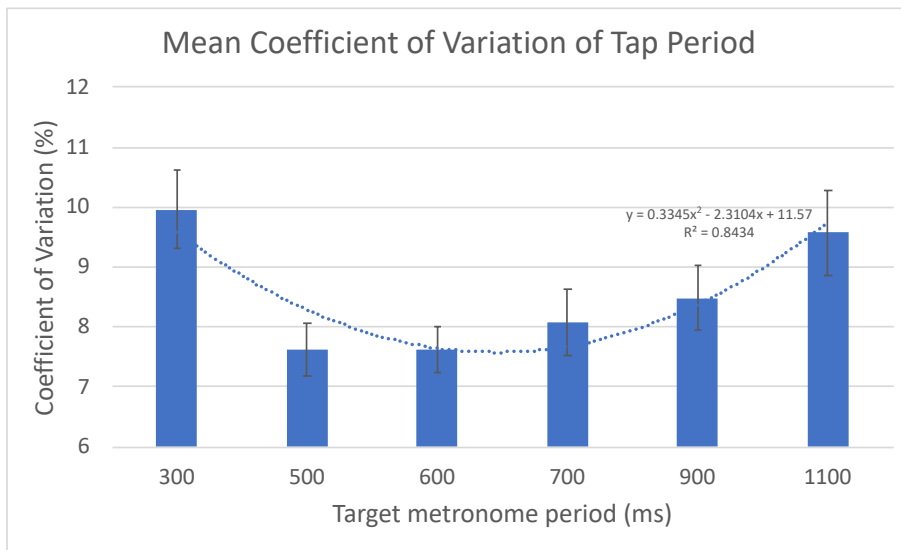


Figure 43 The mean coefficient of variation of the tap intervals as a function of the vibrotactile metronome interval. A quadratic fit is added, reflecting an increase of CV at either end of the target periods tested. Error bars show one standard error of mean.

A one-way ANOVA was performed on the coefficient of variation (CV) versus the target metronome period values. This analysis gave a non-significant p-value of 0.068 ($F(5,100)=2.13$, $p=0.068$), however, it suggested some treatment effect as the proximity of this p-value was close to the significant level of $p<0.05$.

In seeking possible explanations for this, when tapping to a regular beat at different tempi, more variation would be expected at the fastest and slowest tempos (Repp, 2005), thus an increase in CV levels can be expected on either ends of the chosen target metronome periods. This suggested considering a quadratic model.

As ANOVA is agnostic to order, an ordinary least squares (OLS) regression of CV versus the quadratic values of the target metronome periods was performed. This gave significantly stronger evidence (Adjusted $R^2=0.067$, $p=0.01$) implying that a quadratic fit (u-shape) is a better explanation of the data than a horizontal line (where a horizontal line would indicate no treatment effect).

6.4 Discussion

The primary aim of this study was to investigate the ability of healthy participants to tap in synchrony to a haptic rhythm. As mentioned at the beginning of this chapter, there is a lack of information in the literature investigating rhythm perception and production via the haptic modality. Exploring the precise sensorimotor synchronisation limits of haptic rhythm perception is beyond the scope of this research. However, this study provides evidence that participants behave similarly (in the ways explained below) when synchronising their tapping movement to a haptic rhythm compared with previous empirical studies investigating auditory and visual rhythms.

Participants in this study performed best at the 500 and 600 ms period, providing the least variable results, as indicated by the low coefficient of variation value (Figure 43). This result is not surprising as the 500 to 600 ms period is considered to be the preferred and natural pace in synchronisation finger-tapping paradigms (Delevoye-Turrell, Dione and Agneray, 2014). Periods closest to 600 ms (500 and 700 ms) also performed well, with participants on average tapping to a period close to the target period (Figure 41) with significantly lower variability than both the faster and slower tempi tested (Figure 42).

Tapping at slower tempi (i.e. 900 and 1100 ms) is not as accurate, as seen in Figure 41, with participants tapping faster than the target rate. This may indicate approaching an upper IOI limit, where subsequent target events appear disjoint from each other and not as a part of an isochronous rhythm. The behaviour at these IOI is similar to that seen with both auditory and visual rhythms (Repp, 2006b), when approaching the upper (slowest) IOI limit of 1300 ms.

In the auditory and visual cases, subjectively, at these slow tempi, the task of tapping to the rhythm begins to feel difficult, becoming essentially a task of interval estimation (Repp, 2006b). Each tap is performed consciously at the

remembered duration of the previous target event, while any error must be compensated for deliberately. This creates bigger cumulative errors that increase the CV values.

By contrast, when tapping at IOI periods between the upper and lower limit, error correction occurs automatically (Repp, 2005), through a process of entrainment to the external rhythm, keeping the CV value to a lower level.

On average, participants in this study could tap to the fastest (300 ms) target period with high accuracy (as seen on Figure 41). However, at this tempo, high variability was observed (see Figure 42 and Figure 43). This high variability may be attributable less to problems with entraining, and more to problems with physically tapping and fatigue, as participants often remarked they found it difficult to keep tapping at such a fast pace for 30 seconds. This limitation was subsequently rectified for the study discussed in Chapter 7.

Primarily, these results demonstrated that able-bodied people can entrain to a rhythm presented haptically. Less expectedly, but usefully, a simplified version of the protocol was put to new use in the study described in the next chapter for the purpose of screening participants.

In particular, it was used to distinguish between stroke and brain injury survivors who simply may have physical difficulty walking to a rhythm, versus participants who are unable to entrain to a rhythm. This is important because the ability to perceive a rhythm can be affected by injury on certain parts of the brain (Kobinata *et al.*, 2016). In some cases, a brain injury may affect the ability to entrain (Kobinata *et al.*, 2016); and brain injuries can affect perception in particular modalities.

Consequently, a benefit of the simplified protocol adapted from this chapter used for screening is that it allows participants to be identified who are

- a) able to entrain to rhythms;
- b) not impaired in the ability to entrain to rhythm presented haptically.

This is particularly useful as neither of these conditions can be detected via standardised gait assessment tests such as the Rivermead mobility index test, applied in the study discussed in the next chapter. For the above reasons, the procedure of the study presented in this chapter was adapted into a finger tapping test, called the *haptic tap test*, and used as a screening test for hemiparetic participants. The haptic tap test allowed for an empirical indication of the participants' cognitive and perceptual ability to entrain to a rhythm for walking.

6.5 Conclusions

Widespread experiments have established that most people can synchronise their actions to a regular beat at a range of tempi (Repp, 2005). However, the existing empirical evidence relates almost exclusively to synchronisation to auditory and visual stimuli.

This chapter has confirmed recent evidence (Holland, Bouwer and Hödl, 2018) that people can entrain to a haptic rhythm. In the experiment reported in this chapter, a sample of eighteen able-bodied people were shown to be able to precisely lock the frequency and phase of their tapping over an extended period to a haptic rhythm. Following (Repp, 2005), this is clear evidence of entrainment to the stimulus. This chapter has also empirically identified a workable range for able bodied participants for such entrainment. Participants demonstrated noteworthy reduction of their coefficient of variation (CV) when tapping to the middle haptic target tempi of the range tested in this study. This is interesting in at least two ways. Firstly, this identifies a range of tempi at which the participants were able to tap most accurately. Secondly, this offers particularly clear evidence at these tempi using Repp's (Repp, 2006a) criteria as discussed in 2.2.4, page 16.

Clearly the rhythm perception of stroke survivors may differ from that of able-bodied users - indeed, (Patterson *et al.*, 2018) have explored such differences in

some detail. However, as discussed at the beginning of this chapter, given the wide variability of stroke survivors generally, it was decided to use able-bodied people as an informative baseline.

Turning this argument around, we have proposed a simplified version of this protocol as a screening instrument for stroke survivors to measure their ability to perceive and replicate rhythms presented in the haptic modality. As discussed earlier, this provides a useful way to distinguish between stroke survivors with physical difficulties in walking to a rhythm as compared with those whose abilities to perceive or produce rhythms have been neurologically impaired.

Indeed, this instrument developed in this chapter was put to new use in the study described in the next chapter for the purpose of screening participants. This enabled relevant screening not possible with standardised gait assessment tests such as the Rivermead mobility index test (see Appendix 2, page 187), as discussed in the next chapter.

Chapter 7

Study 2: Rhythmic haptic cueing for gait rehabilitation

As discussed in Chapter 2 (page 27), following a stroke or brain injury, many people are left with an asymmetric gait. This can have many adverse health consequences. Rhythmic *auditory* stimulation (Chapter 2, page 33), based on the principle of entrainment (Chapter 2, page 12), is an established gait rehabilitation technique with proven benefits on gait asymmetry.

This chapter reports on a study aimed to investigate the extent to which similar benefits can be obtained for hemiparetic stroke and brain injury survivors by using *haptic*, rather than *audio*, cueing. The study in Chapter 6 established that entrainment through haptic rhythms is possible. A key aim of the present study is to investigate the effectiveness of the haptic modality to promote and use entrainment for gait rehabilitation. However, because of the very different affordances of hearing and touch, there is also a wider purpose: to explore any new effects that may emerge due to considerations such as proprioception, attention and memory.

7.1 Background

As outlined in Chapter 2, brain injury following an accident or stroke can leave people with life changing neurological conditions and a general weakness on one side of the body (discussed earlier in section 2.5.1, page 27). Motor control of one side of the body can then be severely affected with unilateral loss in sensation and muscle coordination of both upper and lower limb.

Motor control deficiencies can lead to spatial and temporal asymmetries between steps in a condition known as “hemiparetic gait”. The asymmetries can cause sufferers of hemiparetic gait to overuse their non-affected (non-paretic) leg, exposing it to higher vertical forces (Bohannon and Larkin, 1985; Mercer *et al.*, 2009), while underuse of the paretic (affected) leg can lead to loss of muscle tone and reduction of bone mineral density (Min *et al.*, 2016). These effects in turn increase the risk of knee and joint problems, hip and bone fractures, and raise the risk of falls (Wen *et al.*, 2010).

As also noted in Chapter 2, walking following an external metronomic rhythm has been shown to improve gait, leading stroke survivors to walk more symmetrically (Thaut, McIntosh and Rice, 1997) and to neglect their affected leg less.

Following the tap test study presented in Chapter 6, there is clear evidence that people generally can perceive and produce accurate motor responses to isochronous tactile rhythms. The study in this chapter is designed to investigate the effects of rhythmic haptic cueing on diverse gait characteristics associated with healthy kinematics and gait patterns. These include spatial characteristics (e.g. stride lengths), temporal characteristics (e.g. step, stand, and swing times) and derivative asymmetries, calculated from the spatiotemporal characteristics using methods discussed in section 2.4, page 24.

7.2 The study

Hemiparetic brain injury survivors involved in the present study were asked to walk a short distance: firstly, without intervention, in order to establish a baseline; then, following an isochronous (regular) haptic rhythm - whose period matched a symmetric version of their natural cadence. Subsequently, any residual effects of walking to the rhythm (i.e. rhythm persistence and the ability to walk to the rhythm from memory) were tested by asking the participants to walk to the rhythm from memory shortly afterwards.

In order to identify quantitative changes in gait, two kinds of data were collected, involving temporal and spatial asymmetry respectively. Temporal asymmetry focuses on measures such as paretic and non-paretic step timings, whereas spatial symmetry focuses on measures such as paretic and non-paretic step length.

Due to limitations on the availability of participants in the context of this research, while temporal data was collected for all twelve participants, spatial data was collected only for six.

As explained in detail below, all spatial data was collected in an optical motion capture facility in Manchester, close to where half of the participants lived. All temporal data was collected by the Haptic Bracelets themselves, which were also used to cue all participants. Those participants not tested in Manchester were tested in Milton Keynes using the Haptic Bracelets alone. However, as discussed below, care was taken to ensure that the experimental context, procedures and data in both locations were commensurable.

7.2.1 Participants

Twelve community-dwelling, community ambulant adults (four female) with chronic hemiparesis (chronic defined as > 6 months since stroke onset) gave written informed consent to participate. Eleven had chronic hemiparesis after stroke, and one after suffering brain trauma following an accident. The age range of this group of participants is shown in Table 3 and Table 4. The time since occurrence of stroke varied from 8 months to 12 years.

Demographic Information	
Age	61.75 ± 7.85 years
Gender	8 males, 4 females
Paretic side	9 right, 3 left

Table 3 Participant demographic information

Participants were recruited through local support groups and by recommendation of private physiotherapists. Inclusion criteria were:

- walking disability, but with retained or subsequently recovered ability to stand and ambulate;
- ability to walk unsupported (but with a walking aid if needed) for a minimum distance of 10 meters; and
- a Rivermead Motor Assessment (RMA) scale score of more than 8.

The Rivermead Motor Assessment (RMA) is a standard and widely used test for assessing functional mobility in gait, balance and transfers after stroke (Williams, 2011). The score of 8 and higher was decided as the inclusion criterion following discussions with physiotherapists. An example RMA score sheet can be found in Appendix 2. Participants were excluded if they had cognitive impairments preventing understanding of the task. Participants could use their assistive devices (ankle-foot orthosis splint and/or cane) in the trials.

Participant Code	Age and Sex	Years since brain trauma	Paretic side	Condition
MMUP01	53 (F)	12	Right	Unknown
MMUP02	57 (F)	0 (8 months)	Right	Hemorrhagic stroke
MMUP03	73 (M)	2	Left	Ischemic stroke
MMUP04	68 (M)	7	Right	Unknown
MMUP05	61 (M)	5	Right	Unknown
MMUP06	55 (F)	4	Right	Ischemic stroke
OUP01	50 (M)	21	Right	Hemiplegic trauma *
OUP02	67 (M)	9	Right	Ischemic stroke
OUP03	60 (M)	2	Right	Hemorrhagic and ischemic stroke
OUP04	73 (F)	1	Right	Ischemic stroke
OUP05	56 (M)	1	Left	Hemorrhagic stroke
OUP06	68 (M)	4	Left	Ischemic stroke and diagnosed with Parkinson's

Table 4 Further demographic information. Participants with "MMU" code took the study at the Manchester location, and "OU" at Milton Keynes. Participants with an "" in the condition column did not have a stroke but sustained brain injury causing hemiparesis from a different cause. Participants who were not sure or chose not to disclose this information were marked with "Unknown". Ischemic and hemorrhagic strokes are briefly described in section 2.5, page 27.*

7.2.2 Study location

The study was carried out in two locations: a fully equipped kinematics lab in Manchester, and a lab specially adapted for this gait study at the Open University campus in Milton Keynes. Both labs were essentially identical in their set up, with a ten meters long straight and unobstructed area where participants could walk in a safe and comfortable manner (both labs are shown on Figure 46, page 132). Six participants (three female) attended the study in Manchester, and six (one female) the study in Milton Keynes.

As already noted, all spatial data was collected in the optical motion capture facility at the Manchester Metropolitan University, where half of the participants were located. The lab is equipped with a state of the art kinematics monitoring system (discussed in section 7.2.4 below), allowing the recording of spatial data in high resolution. The part of the study in Manchester was carried out in collaboration with professionals in physiotherapy nursing and practice, and a technician with experience in gait analysis from kinematics data. Their expertise provided valuable insights during the study. All temporal data was collected by the Haptic Bracelets themselves, which were also used to cue all participants. Those participants not tested in Manchester were tested in Milton Keynes using the Haptic Bracelets alone. Carrying out the study in parallel in two locations allowed for the maximisation of participant recruitment. The lead researcher was present in both locations, during all sessions, to ensure an identical protocol was carried out.

7.2.3 Equipment used

The purpose of the equipment used in this study falls primarily in three categories: firstly, delivery of a series of haptic cues on alternating legs in a stable and appropriate (for each participant) tempo; secondly, recording temporal gait data characteristics from each participant for each leg while they walk; and thirdly (where available) recording spatial gait data.

As described in Chapter 5, the Haptic Bracelets were used for the first two of these purposes; delivering the haptic cues in a stable and carefully controlled tempo while recording in detail temporal characteristics of the person wearing them. The Haptic Bracelets are designed to be worn in pairs with one device near the ankles on the shank on each leg. The same pair of wearable devices was used in both locations to avoid any data discrepancies caused by hardware and sensor calibration. See Chapter 5 for details of design and implementation.

7.2.4 Optical motion capture system

Spatial data were recorded using a Qualisys optical motion capturing system. The system consists of eight optoelectronic cameras, with a sampling frequency of 100Hz. The trajectories of 20 markers placed on anatomical lower limb landmarks, and 4 additional tracking clusters placed on the right and left shank and thigh (see Figure 44), were collected and filtered using a fourth-order zero lag Butterworth low-pass filters, with a 6Hz cut off frequency. Each marker is tracked by the cameras, triangulating its position in space. This allows tracking of motion in three degrees of freedom in millimetre accuracy.

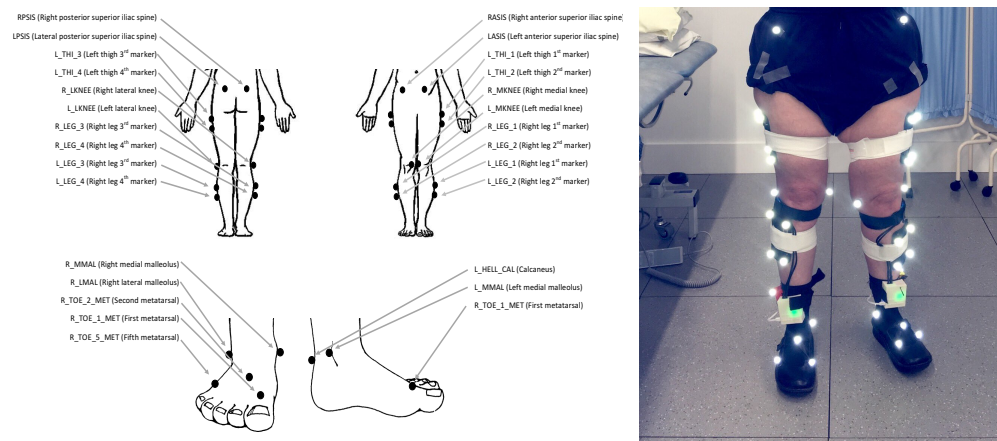


Figure 44 The Qualisys marker setup used for this study is a modified version of a widely-used model for anatomical body tracking called “CAST” (Cappozzo *et al.*, 1995).

7.3 Procedure

7.3.1 Preparation

Participants were asked to come to the lab wearing their normal everyday clothes and comfortable shoes. For reasons explained above (see section 7.2.2) the study took place in two locations. An identical procedure was followed in both locations, but because of the way kinematics data are collected from the motion capture system (i.e. placing markers on the body), three additional preparatory steps were required for participants in Manchester to meet the needs of the optical motion capture system. Namely, they were asked to change into shorts; 30 to 45 minutes were required for a trained technician to place all the markers on their body (with position of markers as seen in Figure 44); and biometric measurements were taken (i.e. height and weight).

In both locations, the Haptic Bracelets were attached, via Velcro straps, onto the shank of each leg near the ankle. The vibrotactile - the part of the device that gives the haptic cue - was attached using another Velcro strap near the knee (as discussed in chapter 5: see Figure 45 below for exact placement).

The placement of the vibrotactile was initially based on the suggestion of physiotherapists participating in the technology probe study discussed in Chapter 4 (page 60). However, this decision was later revealed to be based on a conflation by the physiotherapists of entrainment with stimulus response. Nonetheless, it was subsequently decided to keep this placement for this study for two main reasons:

- proximity to major nerves, giving the tactile cue a good chance to be felt;
- having the vibrotactile unit away from the IMU of the Haptic Bracelet helps to minimise unwanted noise in the gait data.

Participants in Milton Keynes had simpler preparation than those in Manchester: they did not have to wear any kinematics markers, and could simply wear a pair of Haptic Bracelets over their everyday clothes¹².



Figure 45 Vibrotactiles strapped on participant's leg using Velcro straps.

7.3.2 The haptic tap test

As proposed in Chapter 6, before the first trial, all participants were asked to take a haptic rhythm perception test; the *haptic tap test*. The haptic tap test is an adapted version of the procedure used in the haptic rhythm perception study discussed in Chapter 6.

This test aims to assess people's ability to perceive and replicate a rhythm (albeit by tapping) perceived via the haptic modality. This ability can be affected by injury to certain parts of the brain (Kobinata *et al.*, 2016). Such a deficit may go undetected by medical professionals and is not identified by standardised gait assessment tests such as the Rivermead mobility index test.

¹² An exception was made if a participant arrived at the study location already wearing shorts or a skirt.

The haptic tap test follows identical setup and a shortened procedure to the study described in Chapter 6. For the present test, participants were asked to tap with their index finger in time to a range of rhythms. The rhythm was delivered haptically on the paretic wrist, using a wired version of the Haptic Bracelet (see Figure 38, page 109). Tapping was performed by the non-paretic hand in order to avoid any physical constraints due to hemiparesis, or the effects of haptic masking (Bouwer, Holland and Dalglish, 2013). Haptic masking describes situations where haptic sensation is temporarily muted by adjoining muscle movement. Participants were all tested with rhythmic periods of 500, 600 and 700 ms. These periods showed the lowest variability of response in the haptic rhythm perception study (Chapter 6). Based on experience in Chapter 6, to minimise participants' fatigue, each trial lasted just 20 seconds. The ability to tap was observed visually during the task and was also analysed using the data analysis scripts discussed in Chapter 6. Flawless performance was not required: a general ability to keep in time with the beat was sufficient to pass the test.

A single candidate participant in Milton Keynes (OUP06) failed the haptic tap test. All of the other participants automatically continued onto the gait trial.

OUP06 presented an exceptional case: this participant had Parkinson's in addition to hemiparesis. The haptic tap test was designed for those with hemiparesis alone. Unlike those in this target group, Parkinson's patients are liable to have tremors in both hands. Thus, for such exceptional patients, the haptic tap test cannot reliably distinguish between the lack of ability to entrain mentally and the lack of reliable tapping ability. Although this candidate participant failed the test, the possibility remained that he could mentally entrain, and that he might benefit from the trial. Consequently, for this exceptional reason, OUP06 also continued onto the gait trial on a provisional basis.

7.3.3 Walking to the rhythm trials

This study followed a repeated measures design with three conditions: “baseline”, “cued” and “post”, as described in section 7.2. The participants were asked to walk the length of a 10m runway six times for each condition.

Baseline condition

The initial condition allowed each participant’s baseline gait to be measured, including mean step time. The mean step time was used to set the period of the haptic metronome for the subsequent “cued” condition – subject to any final adjustments, as discussed below.

Choosing the period for the cued condition

This approach to choosing the cueing period was motivated by the literature, as now discussed, but with scope for practical adjustments to cope with the focus on hemiparetic participants. One of the underlying neurological principles defined in the RAS rehabilitation technique (discussed in 2.6.2, page 31) is to entrain steps to an external rhythm that exactly matches the preferred (uncued) cadence of the patient. Independently, Roerdink (Roerdink *et al.*, 2011), working with elderly able-bodied participants, found optimal performance when cueing with a regular period close to each individual’s naturally preferred cadence. As discussed in Chapter 5, cues in the present study were delivered to alternate legs - evidence from auditory cueing emphasises the benefits of this approach (Roerdink *et al.*, 2009).

Bearing this alternation in mind, in the case of hemiparesis, the *average* period, calculated from a hemiparetic individual’s preferred pace can be too fast for the slower paretic leg to follow, suggesting that some fine adjustment of the period may be desirable. Also, some participants needed to apply conscious effort to walk naturally, and thus some might feel less confident when asked to

undertake an additional task while walking. For these two reasons, possible fine adjustments to the period were allowed.

For these reasons, before walking to the external rhythm, in order to find a comfortable period close to the preferred period, participants were variously asked to tap their foot while sitting down, or to step in place while standing up, or just walk around following the rhythm, as was most convenient for them. This familiarisation period allowed final adjustments to the period and to the intensity of the haptic cue.

Findings from the technology probe study (section 4.2, page 60) highlighted the importance of clear instructions on entraining steps to a rhythm.

Participants were instructed to time the steps of their non-paretic (i.e. “good”) legs to the beat, but not to worry about their paretic leg. They were encouraged to feel the rhythm in a similar way to feeling the rhythm of a song. After testing various instructions through trial and error, this instruction was found to generally lead to a more balanced gait than asking participants explicitly to time the steps of *both* legs to their respective beats.

Here an interesting issue arises. One might be tempted to engineer a cue where the ratio of step periods between legs lay at some intermediate point between the baseline asymmetry and a perfectly balanced symmetry. However, considering the theory of entrainment, and from observations during in-lab pilot testing, participants generally find it much easier to entrain to a regular beat than an irregular or “swung” beat (in musical terminology). It is also generally far easier to remember a regular beat.

Cued condition

Once participants confirmed they understood the instructions they were asked to walk six 10m lengths following the haptic rhythm. Temporal data and, in the case of participants in Manchester, spatial data were recorded for each walk.

Post condition

Immediately following the ‘cued’ condition, and after a short five-minute break, each participant was asked to repeat a further six 10m walks without haptic cueing. The purpose of this ‘post’ condition was to investigate any residual effects of walking to the rhythm. This was inspired by literature on Parkinson’s disease reporting rhythm persistence (Thaut *et al.*, 2001; Nieuwboer *et al.*, 2007) and also comments from the participants during the *technology probe study* described in Chapter 4, page 60. In the technology probe, a participant noted how the rhythm stayed in their memory; “*If it is switched off [...], it’s still there. [...] in my head*” (comment from P4 – page 68).

Even though a short five-minute break was scheduled between conditions, participants were told they could take a break at any point during the study. Chairs were placed on either end of the 10m runway for comfort and safety. Figure 46 below shows the lab setup in both locations.

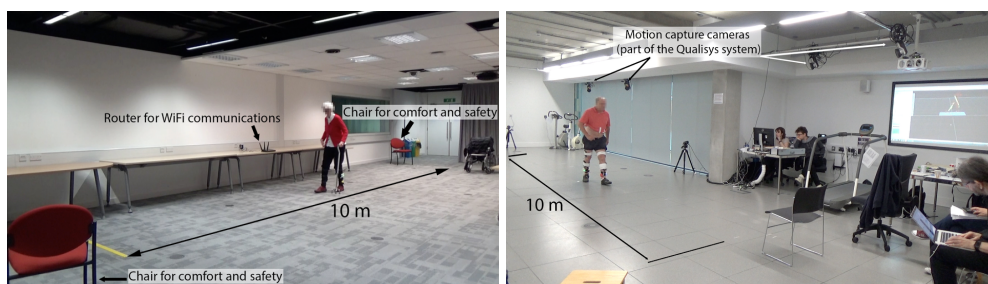


Figure 46 Participants during a 10m walk trial. Left shows the OU and right the MMU location.

The study concluded with a short discussion based on the participant’s experience about walking with the haptic rhythm. All trials were video recorded for later review by expert physiotherapists, since, even if they were in the room at the time, they often concentrated on participant’s safety instead on subtle changes in their gait pattern and body movement.

7.4 Data analysis and results

In this study, temporal and spatial data were recorded and analysed. Temporal data refers to times between events (e.g. time between subsequent heel strikes) and gait characteristics that can be calculated from these timings (e.g. the overall temporal asymmetry (OTA) values as seen in Chapter 2, page 24).

Spatial data, on the other hand, indicate characteristics relevant to space, such as stride lengths, and combinations of space and time (i.e. velocity).

Spatial and temporal data collected during the ‘cued’ and ‘post’ conditions were compared against the baseline, looking for any effects that entrainment to haptic rhythmic cueing had on the participant’s gait. Comparing the data against the baseline allowed each participant to act as their own control, making clear any walking effects that were caused by the cue.

As previously discussed, the present study took place in two locations. Temporal data were recorded and analysed from participants of *both* locations using the Haptic Bracelet’s on-board sensors. However, spatial analysis was performed only on data captured in Manchester by the optical motion capture system. Finally, qualitative data from both locations were documented from observations during the study and comments from participants and physiotherapists.

7.4.1 Outlier exclusion

As in the haptic tapping study (Chapter 6), data from individual steps (temporal and spatial) were examined for outliers.

Note that some participants would occasionally break their step mid-trial and take a small number of short shuffling steps. These steps were associated with much shorter step times, shorter step lengths and lower velocity than the rest of the trial. Such episodes could be clearly differentiated in the data due to the exceptional interruption of an otherwise more or less regular pattern. Note that, because steps are measured from heel-strike to heel-strike, one subsequent step

of each leg after each such episode would also be discarded to allow a reliable starting point for subsequent measurement to be registered. Consequently, in the data analysis, these events would be treated as outliers and discarded. The effect of this was to give clean data excluding interruptions.

Outlier values were defined as any values lying 1.5 times the interquartile range beyond the first and third quartile (see section 6.3.1 (page 112) for the outlier calculation equations and a full explanation). For characteristics that jointly contribute to the step time (i.e. swing and stance times), if either value was considered to be an outlier, both values were removed from the analysis.

One participant (OUP06) withdrew from the study as it was unclear that he could complete the trials in a safe manner. This participant exhibited high levels of fatigue causing him to become less stable after the first few trials. The lead researcher stopped the study to prevent any risk of injury.

7.4.2 Post-trial analysis of the haptic tap test

As described in section 7.3.2, prior to the walking trials, all participants carried out a haptic tap test to check their general ability to keep in time with a beat. Subsequent to the walking trial, the results of this test were more formally analysed. The mean time between successive taps was calculated for each target tempo for each participant. The resulting mean tap periods for all three target periods are summarised in Figure 48.

Participants in general demonstrated synchronisation to the target rhythm, though some mentioned fatigue and physical difficulties during the tapping task, as reflected by the relatively large standard deviation values. However, the tapping task did not give evidence for exclusion, as all demonstrated adequate rhythm perception ability (though see section 7.3.2 for an edge case).

Interestingly, some participants continued tapping for at least once tap after the last tactile cue (see Figure 47 below for an example). This ‘last tap’ was in time with the previous taps in the series, indicating anticipation – a

neurological principle discussed in section 2.6.2 page 31, and a key part of entrainment. This provides further clear evidence of entrainment during the tap test. The time of the last tap is shown as a green dot in Figure 48 for each participant.

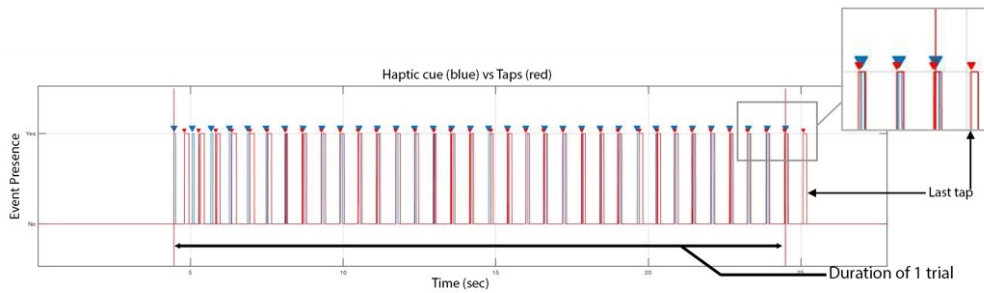


Figure 47. Tap data from one trial showing the last tap after the tactile rhythm stopped; an indication of entrainment. Blue triangles signify the beginning of a haptic cue, and red triangles indicate the beginning of a tap.

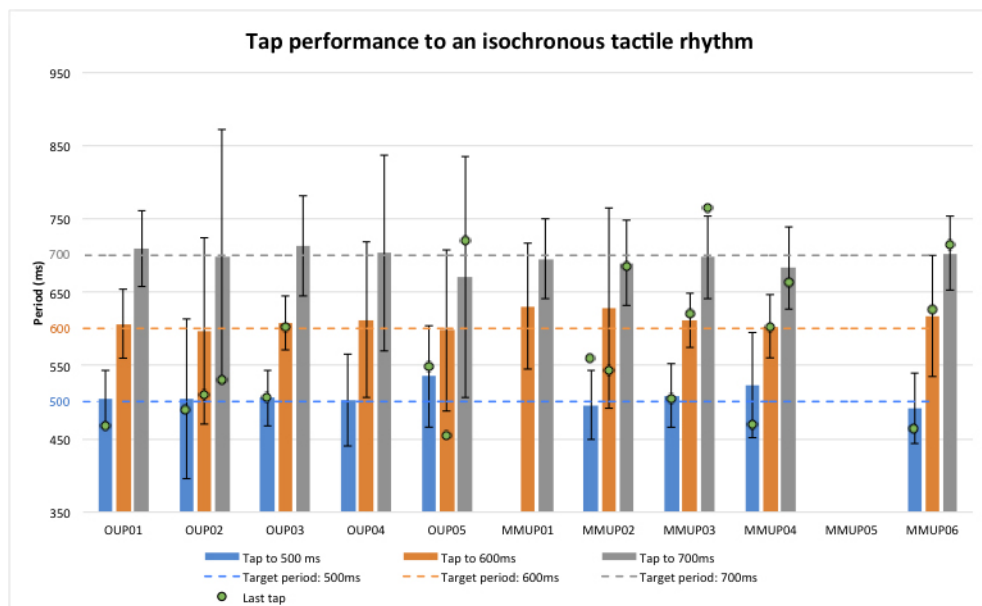


Figure 48 Tap test results for all three target periods: 500, 600 and 700 ms. The error bars show one standard deviation from the mean. Green dots indicate the time of the last tap after the tactile rhythm ended, as discussed in the text. (Due to technical difficulties, results from MMUP01's first trial at 500 ms, and all trials of MMUP05 could not be reported).

7.4.3 Temporal data

As previously discussed, paretic and non-paretic step timings were determined from initial footfall contact by the Haptic Bracelet's on-board sensors.

Analysing data from different sensors and combining the information together allowed for the analysis of stance and swing times. From these, the overall temporal asymmetry (OTA) ratio value (see Chapter 2, page 19) was calculated for every participant in every condition (baseline, cued and post). The way data from the Haptic Bracelet's on board IMU was analysed is described in Chapter 5, page 101.

The average reduction on the OTA values across all participants indicates an overall improvement, with the OTA value approaching normative asymmetry levels – normative range: 0.9-1.1; as defined in (Patterson *et al.*, 2008). The results are summarised in Figure 49 below.

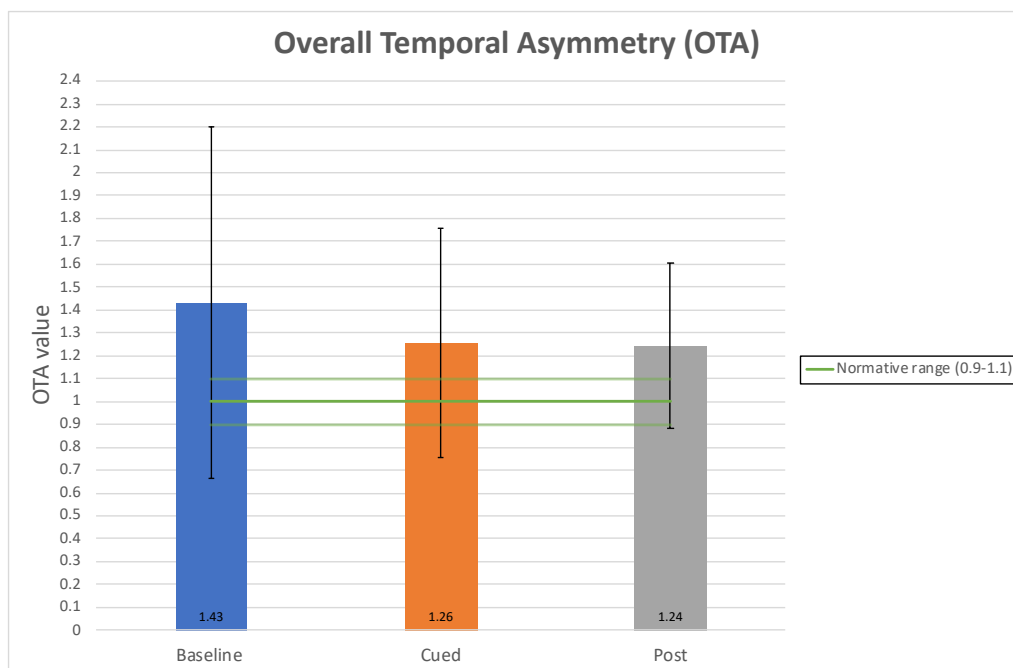


Figure 49 Overall temporal asymmetry (OTA) values for all three conditions: baseline, cued and post. The figure includes normative levels indicating healthy walking asymmetry. Error bars show one standard error of mean

However, the inherent wide variability between individual stroke and brain injury survivors meant a wide range of OTA values; as shown by the error bars in the figure above. In order to statistically compare the baseline overall temporal asymmetry (OTA) values with both the ‘cued’ and ‘post’ conditions respectively, paired-samples t-tests were conducted. Despite the reduction observed in the average OTA value for both the ‘cued’ and ‘post’ conditions compared to the baseline (Figure 49), neither condition reached a level of statistical significance.

More specifically, there was not a significant difference in the OTA values in the ‘cued’ ($t(10)=1.23$, $p=0.25$) or the ‘post’ ($t(10)=1.16$, $p=0.27$) conditions.

Triangulation of temporal data

For reasons detailed in section 7.2.2 above, motion data concerning gait characteristics of only six out of the eleven participants were captured by both the prototype Haptic Bracelet system and the Qualisys system (a commercially available optical motion capture system).

Capturing these data from two independent systems allowed for data and methodological triangulation (see section 3.4, page 46) as the two independent systems used fundamentally different methods to gather data (motion sensor data from the Haptic Bracelets versus optical data from the Qualisys) from the same events, at the same time.

The difference in the values produced by the two systems for each condition is less than 3% (2.7%, 0.7%, 2.8% respectively), indicating general agreement between the two systems. In the later analysis (Page 138), changes were required to be greater than $\pm 5\%$ to be considered meaningful.

The graph in Figure 50 below summarises the *temporal* data of six participants measured simultaneously by both systems.

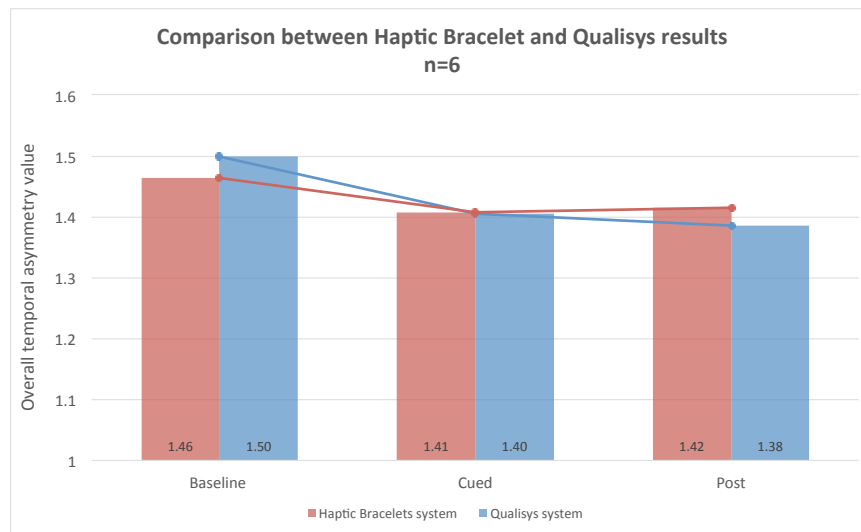


Figure 50 Comparison between data analysis results from the Haptic Bracelet monitor unit (red) and a Qualisys motion capture system (blue).

Methodological note: comparing baseline, cued and post conditions

Due to the high degree of variability between survivors of hemiparetic stroke, and the relatively small number of participants, it is unclear that the most useful information to be extracted from the results will take statistical form. Rather, a great deal of rich information may be available from considering individual cases in detail case by case. Statistical results are considered first below, followed by individual cases.

Consideration of individual results

Reflecting the inherent wide variability between individual stroke and brain injury survivors as noted above, changes to the overall temporal asymmetry (OTA) value were normalised by calculating *percentage* changes from each individual's baseline value. *Negative percentage* values indicate *beneficial* change – i.e. approach to normative value range of 0.9 to 1.1. These data are shown in detail in Table 5, graphed in Figure 51, and summarised for clarity in Figure 52.

Participant code	OTA			OTA percentage change from baseline (%)	
	Baseline	Cued	Post	Cued	Post
MMUP01	1.32	1.23	1.51	-6.99	14.37
MMUP02	1.08	1.06	1.04	-1.94	-3.89
MMUP03	2.27	2.46	1.83	8.46	-19.16
MMUP04	1.11	1.04	1.25	-6.66	12.30
MMUP05	1.84	1.58	1.64	-14.11	-10.88
MMUP06	1.16	1.07	1.22	-7.36	5.13
OUP01	0.85	0.92	0.88	-7.72	-3.06
OUP02	1.14	1.14	1.18	0.44	3.80
OUP03	3.32	1.75	1.56	-47.35	-52.93
OUP04	0.79	0.79	0.80	-0.04	0.17
OUP05	0.86	0.76	0.74	11.68	14.01

Table 5 The overall temporal asymmetry (OTA) values of all participants in all three conditions. OTA is calculated using the equation described on section 2.3.2, page 19. Last and second to last columns show the change from the baseline towards the normative range of symmetry (0.9 - 1.1), representing the healthy portion of the population. Negative values indicate improvement in symmetry.

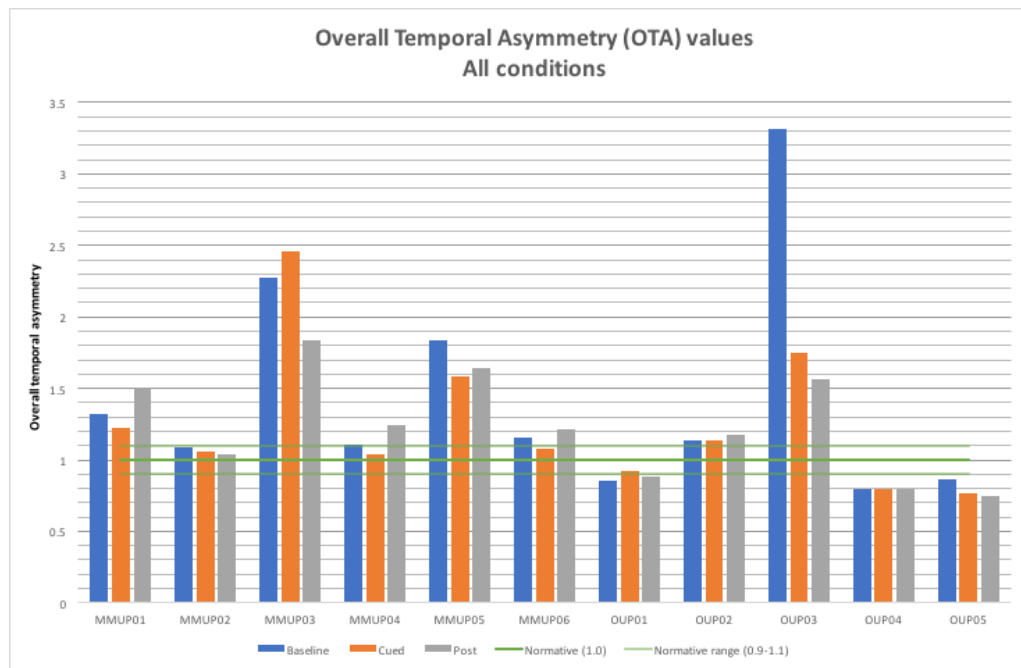


Figure 51 Graphical representation of OTA values shown in Table 5. Perfect symmetry (1.0) and normative asymmetry levels in the range of 0.9-1.1 are shown by horizontal green lines.

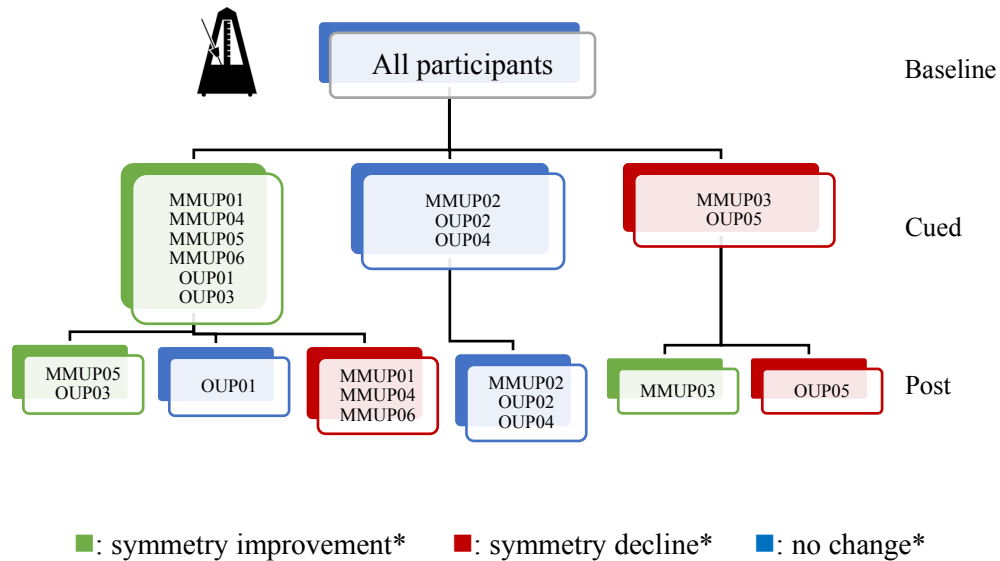
Temporal data results summary

In this study, essentially three outcomes were possible for the ‘cued’ and ‘post’ conditions; a participant’s OTA could improve compared to the baseline, worsen, or stay the same. Alterations of the OTA were considered meaningful if their magnitude was of more than $\pm 5\%$ compared to each individual’s baseline.

Referring back to Table 5 and Figure 51 (summarised perhaps most clearly in Figure 52 below), six out of the eleven brain injury survivors participating in this study exhibited immediate improvement in their gait with their OTA value decreasing towards better symmetry in the ‘cued’ condition. From these six, two maintained a more symmetric OTA value in the ‘post’ condition, three became worse, with their OTA value increasing, while one participant returned back to his baseline level of asymmetry.

Two of the eleven participants became more asymmetric during the ‘cued’ condition, with their OTA value increasing compared to their baseline. From these two participants, one (OUP05) maintained a more asymmetric OTA value in the ‘post’ condition while the other (MMUP03) showed a big improvement compared to his baseline.

Three participants did not show any change in their OTA value in either the ‘cued’ or the ‘post’ condition. These data are summarised in Figure 52 below.



*compared to the baseline of each individual

Figure 52 Participant distribution based on their OTA percentage change compared to baseline. Green indicates beneficial change of more than 5%, red indicates negative change and blue no change.

7.4.4 Spatial data

Spatial data usefully complement temporal data for assessing changes in gait symmetry. The step length and velocity (calculated using step lengths and time of travel) are valuable metrics for assessing the therapeutic effect of rhythm in gait rehabilitation (Thaut, 2007; Patterson *et al.*, 2010; Thaut and Abiru, 2010).

As mentioned previously, spatial data were captured for six out of the eleven participants. This involves markers placed on anatomic relevant locations on the participants' body (see section 7.2.4). However, for accurate tracking, each marker must be in view to at least two of the eight cameras at all times. When line of sight to marker is occluded for all but one camera, the system applies a best estimation of the path based on previous motion. This can introduce inaccuracies.

Occlusions arose in the study when some participants needed to use a walking stick during the trials. One participant not only had a walking stick, but also, due to a recent history of frequent falls, had two carers walk alongside and

behind him for safety (see Figure 53). The carer walking behind the participant was also pushing a wheelchair to catch him in case of a fall – a common practice in gait rehabilitation.

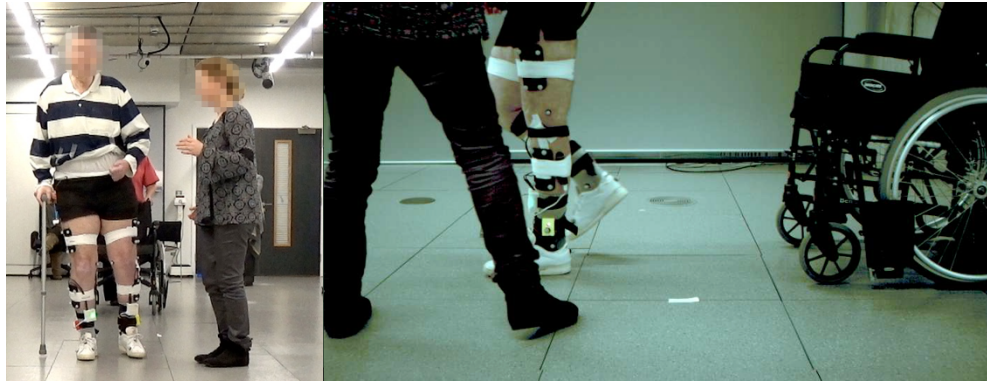


Figure 53 Optical markers required by the Qualisys motion capture system were often blocked by carers walking next to the participants for safety reasons or walking aids used by participants. This potentially introduced inaccuracies in the data when considering full kinematics analysis.

In addition to the marker occlusion limitation, the particular optical tracking installation used could accurately capture kinematic data only from a relatively confined area (called the *capture volume*) where the cameras were focused. More specifically, accurate data from the combined set of markers in the “CAST” model seen in Figure 44 (discussed on page 126) could be captured only in the middle 4 or 5 m of the 10m runway. This capture volume equated roughly to around three steps for each leg. To minimise the effects of this limitation, a single marker was tracked over a longer volume (placed on the heel – marked as HELL_CAL in Figure 44, page 126). This single marker was found retrospectively to have good visibility for at least eight of the ten meters of the runway for all six participants. By contrast the temporal data captured by the Haptic Bracelets on-board motion sensors was available for the full range of motion.

Processing of spatial data

In analysing the spatial data, possible outcomes likely to be of interest to physiotherapists and other health professionals include changes in spatial gait asymmetry, step lengths, and walking speed.

Using a Matlab script developed for this purpose, the leg movement characterised by a single marker movement placed on the heel of each leg (Figure 44, page 126) was analysed, and step lengths calculated. The reason for using data from a single marker is discussed in detail in the section above.

Figure 54 below shows the distance the optical marker moved over time in one trial of one participant, thus the gradient of this graph denotes velocity (distance/time). Note that the velocity represented by this gradient is what might be called “foot flight velocity”; this is because overall walking speed depends not just on the velocity of the foot when it is in the air, but also on how long the foot spends stationary between steps – however steps were taken in the data processing to relate this more closely to walking speed (see section 7.4.1, page 133).

When the gradient of the graph in Figure 54 is zero (i.e. the blue line is horizontal), the foot is stationary, indicating the end of a step. Changes in gradient (marked with vertical black lines) were used to identify when the foot moved, allowing for accurate average stride length calculations.

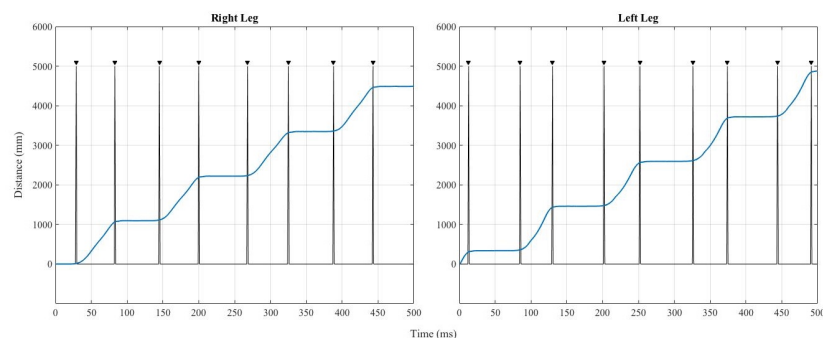


Figure 54 The blue line indicates marker movement. The gradient of the blue line represents velocity. Black vertical lines indicate changes in the graph's gradient, hence, the start and end of individual steps.

Two aspects of spatial data were analysed: firstly, step length in the cued and post conditions were compared against the baseline, and secondly, the spatial asymmetry value was calculated, using the same formula discussed in Chapter 2, page 24 for overall temporal asymmetry (OTA).

Figure 55 demonstrates visually the difference in gait pattern between the paretic and non-paretic leg seen in one trial. The non-paretic leg lifts higher and in a smoother, more uniform arc, while the paretic leg stays closer to the ground, lifts for a shorter period, and is almost dragged along.

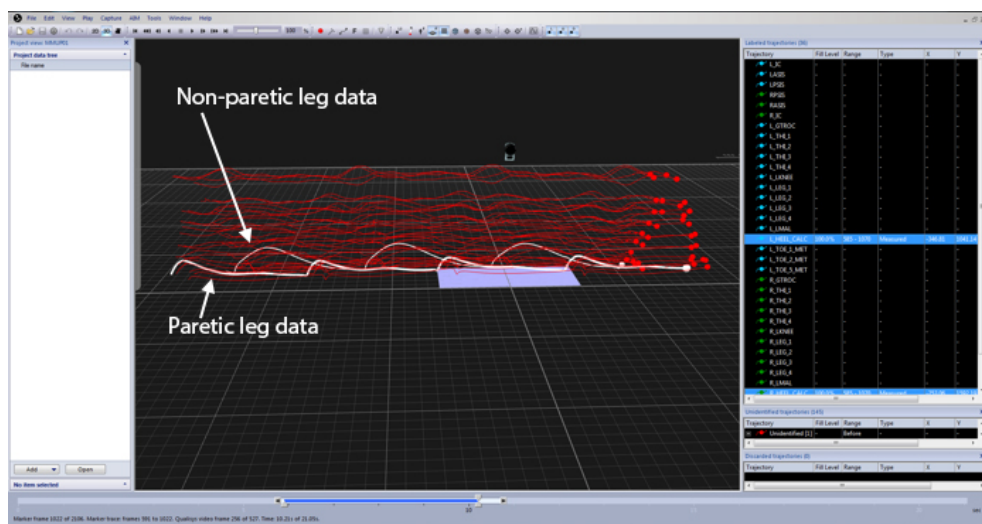


Figure 55 Qualisys Track Manager (QTM) data. White traces indicate heel markers (red traces show markers on other parts of the body – the red dots on the right show to which body location each trace corresponds). Observing the path of these markers shows the non-paretic (left) leg following a higher, more uniform arc while the paretic leg remains closer to the ground following a much shorter arc.

As with consideration of the temporal data, due to the great variability between participants, useful information can be extracted by considering both changes in mean values and changes in individual cases. Changes in mean values are considered first.

When walking following the rhythm in the cued condition, the mean spatial symmetry showed a small improvement compared to the baseline – see Figure 56.

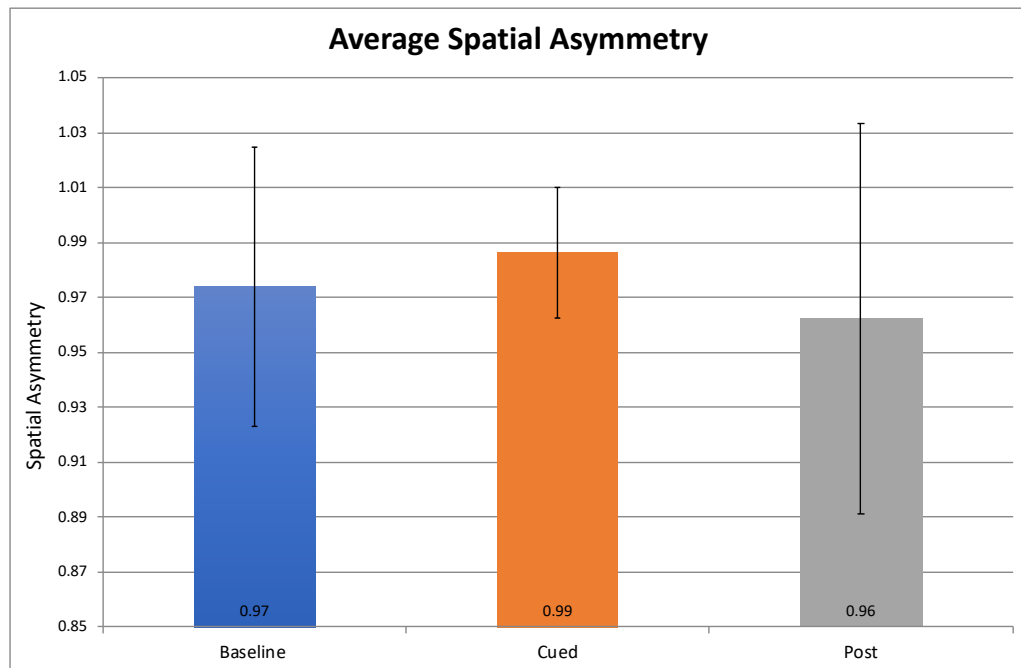


Figure 56 The mean spatial asymmetry from all six participants in the three conditions tested: baseline, cued and post. Spatial asymmetry is calculated by dividing the average stride length of the paretic leg by the average stride length of the non-paretic leg. Higher scores indicate better symmetry – 1.00 is a perfect score. Error bars show one standard error of mean.

This small improvement is further evident by the reduction in the standard deviation, shown by the smaller range covered by the error bar in the ‘cued’ condition.

Interestingly, by contrast with the change in symmetry, the average stride length *decreased* by 16 mm in the cued condition compared with the baseline and increased by almost 50 mm in the post condition over baseline (Figure 57). Bearing in mind that all participants in this study were hemiparetic stroke survivors with various degrees of cognitive and motor control deficiencies, it may be that the increased cognitive load of attending to the rhythm led to shorter stride lengths. A related but slightly different argument might be that asking participants to walk while following the haptic rhythm may have led to more conscious attention on their movement, increasing cognitive load and causing them to take shorter and more careful steps. Further light is cast on

these hypotheses by the observation of considerably longer steps in the post condition, where the external haptic rhythm was removed, and participants were asked to walk to the rhythm from memory. This issue is revisited in 7.5.2.

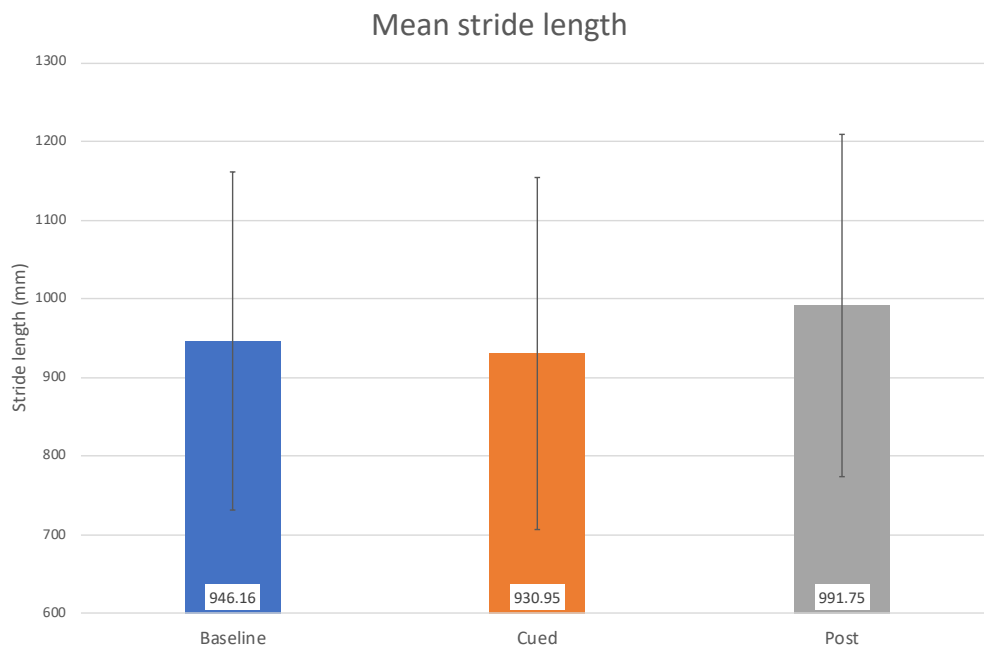


Figure 57 Average stride lengths for all three conditions: baseline, cued and post. Stride lengths are calculated from optical marker data and analysed using bespoke algorithms. Error bars show one standard error of mean.

The standard error value (indicated by the error bars in the figure above) remained on similar values for all conditions; $\pm 215\text{mm}$, $\pm 223\text{mm}$, and $\pm 217\text{mm}$. This suggests that on average, stride length did not become more or less variable during either the ‘cued’ or the ‘post’ condition when compared to the baseline. Unsurprisingly, in all conditions, the mean paretic stride length was shorter than the non-paretic stride length – see Figure 58.

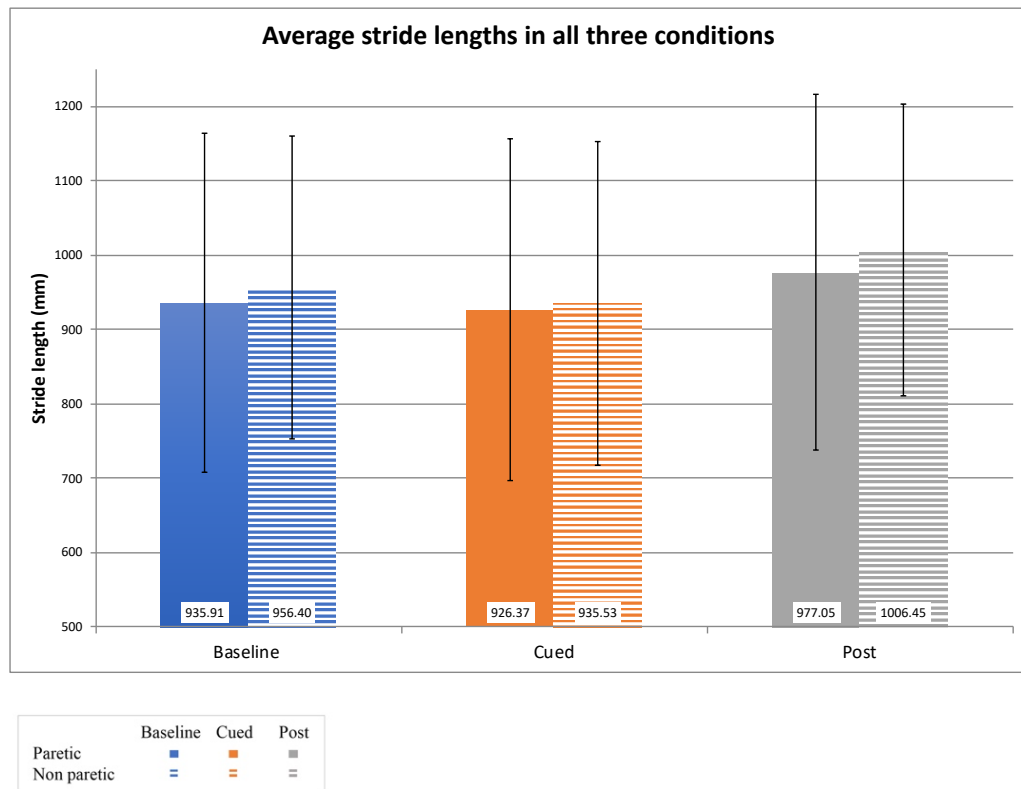


Figure 58 The average stride lengths in millimetres from all six participants in the three conditions tested: baseline, cued and post. Data were captured by a Qualisys motion capture system tracking a single marker on the heel of each foot. In this figure, solid colour indicates values for the paretic leg. Error bars show one standard error of mean.

Further consideration of mean spatial changes is discussed in detail in the discussion section (7.5.2, page 155).

As previously argued, in situations with great individual variation, it is important to consider and analyse individual results from all participants before drawing firm conclusions. These results are shown on Table 6 and Figure 59. For these results in terms of *differences*, see Table 7.

Participant code	Stride lengths (mm)					
	<i>Paretic Leg</i>			<i>Non-Paretic Leg</i>		
	<i>Baseline</i>	<i>Cued</i>	<i>Post</i>	<i>Baseline</i>	<i>Cued</i>	<i>Post</i>
MMUP01	1106.71	1086.47	1110.63	1105.03	1080.39	1108.21
MMUP02	812.59	1001.08	1092.22	801.57	997.30	1090.41
MMUP03	647.08	586.77	717.40	685.90	621.79	749.60
MMUP04	1146.11	1182.15	1193.77	1148.95	1194.59	1208.98
MMUP05	743.89	709.52	630.48	841.82	727.63	767.68
MMUP06	1159.07	992.25	1117.81	1155.14	991.48	1113.84

Table 6 Stride lengths of six participants using optical marker data from a Qualisys motion capture system. Stride lengths are measured in millimetres. For this table in terms of differences see Table 7.

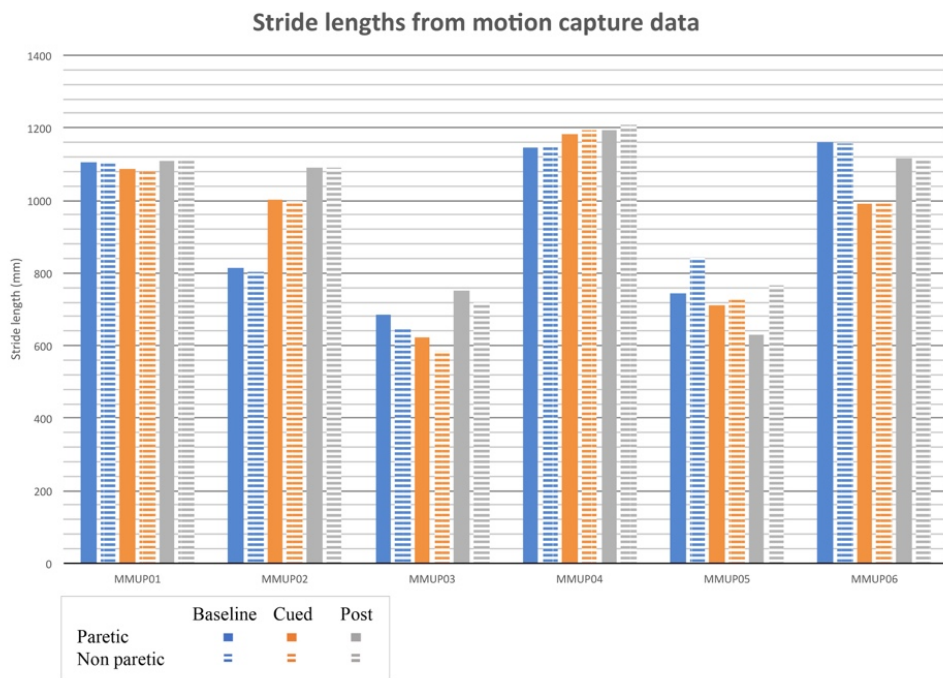


Figure 59 Graphical representation of data from Table 6.

To assist with clarity of the results, the *percentage changes* for the ‘cued’ and ‘post’ conditions when compared to the baseline is shown in Table 7.

Participant code	Stride length change compared to baseline (%)			
	<i>Paretic Leg</i>		<i>Non-Paretic Leg</i>	
	<i>Cued</i>	<i>Post</i>	<i>Cued</i>	<i>Post</i>
MMUP01	-1.83	0.35	-2.23	0.29
MMUP02	23.20	34.41	24.42	36.03
MMUP03	-9.32	10.87	-9.35	9.29
MMUP04	3.14	4.16	3.97	5.22
MMUP05	-4.62	-15.25	-13.56	-8.81
MMUP06	-14.39	-3.56	-14.17	-3.58

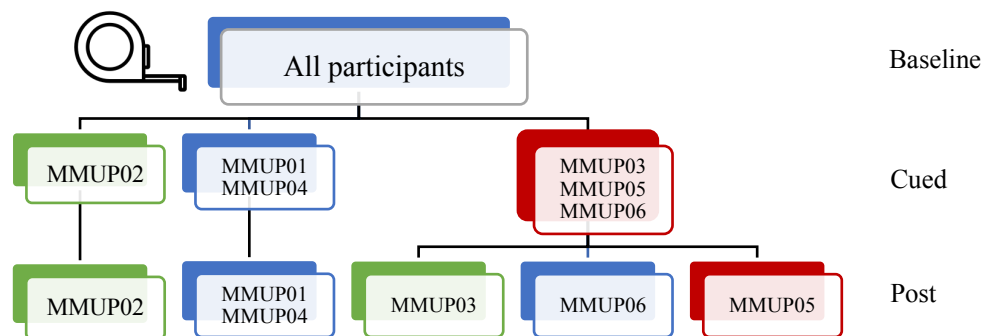
Table 7 Percentage difference of stride lengths compared to the baseline values. Changes below $\pm 5\%$ are not considered meaningful.

Spatial data results summary

In this section, individual changes in spatial data are summarised. For three of the six participants, the mean cued stride length was shorter than the baseline by more than 5%. One participant walked with longer stride lengths when cued and two did not show any change of more than 5% when walking with the cue.

When walking to the rhythm from memory in the post condition, the stride lengths of two participants increased, one decreased, and three showed no change outside 5%. Interestingly, the same two participants were unchanged during cueing and post.

This data is summarised conveniently in Figure 60.



■: increased stride length* ■: decreased stride length* ■: no change*

*compared to the baseline of each individual

Figure 60 Participant distribution based on their stride length percentage change compared to baseline. Green indicates an increase of stride length, red indicates shorter stride length (in both cases >5%) and blue no change.

Walk velocity

In this section, as previously, mean results are considered first followed by consideration of individual changes.

Mean walk velocity for each condition was calculated for each participant by averaging heel marker velocity from all six trials. For the purposes of considering means over all participants (Figure 61) averages were further taken across both legs and all six participants. Paralleling the changes to stride lengths discussed in the previous section, mean walk velocity compared to baseline decreased during the cued condition, and increased during the post condition (Figure 61). The hypotheses noted earlier (page 145) concerning sensorimotor deficiencies and increased cognitive load may apply to this observation.

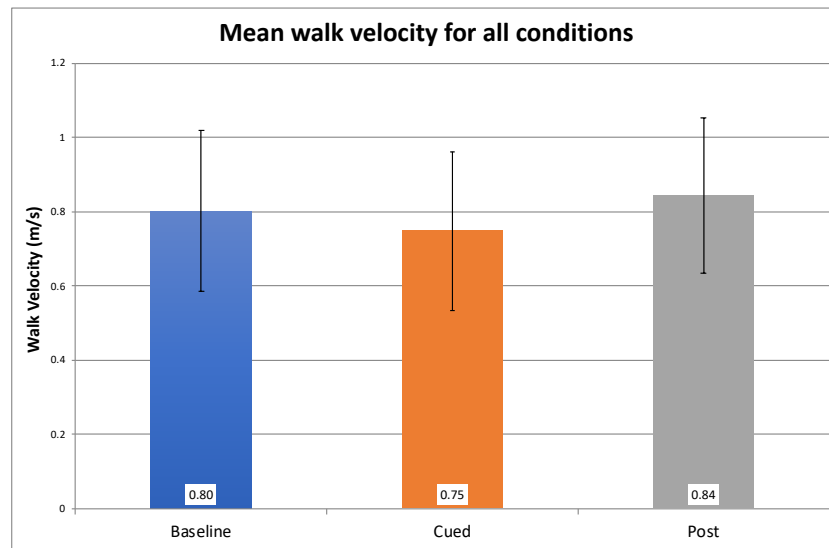


Figure 61 Walk velocity for all participants in all conditions. Velocity was calculated using bespoke algorithms from data collected from a commercial optical tracking system. Error bars show one standard error of mean.

Individual changes to walk velocity are presented in the series of charts and tables below, starting with Figure 62.

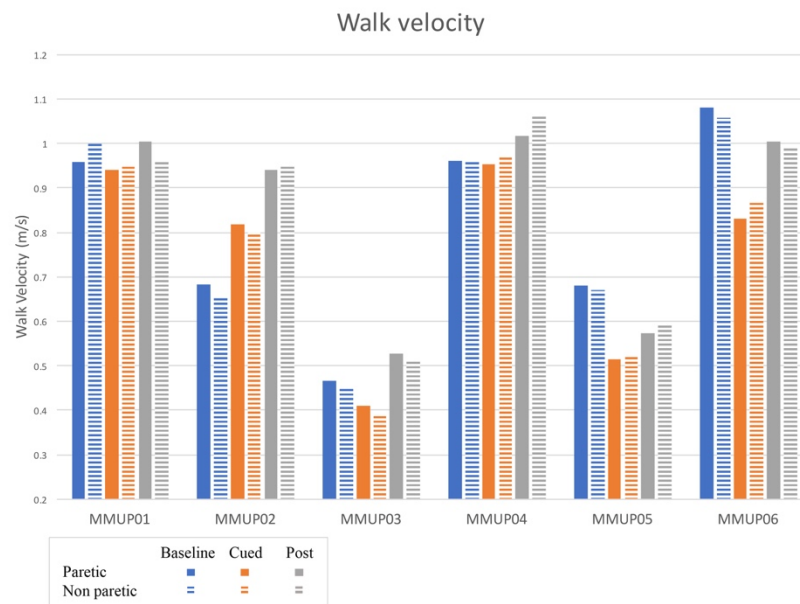


Figure 62 Individual walk velocity data for all participants in all three conditions.

One participant walked faster in the cued condition, three more slowly, and two showed no change of over 5% from their baseline.

The effects of the rhythmic haptic cue on the participants' velocity is summarised in Figure 63 below.

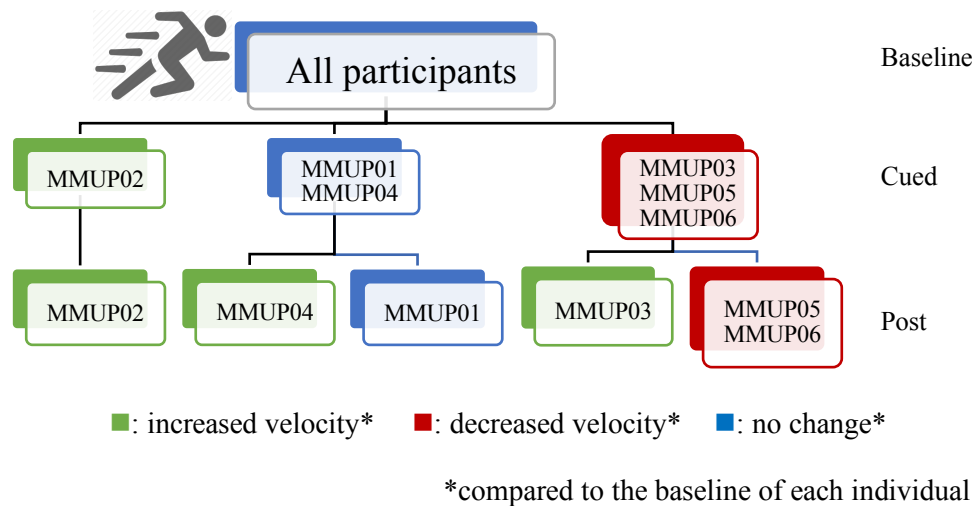


Figure 63 Participant distribution based on the percentage change of their velocity compared to baseline. Green indicates an increase of velocity, red indicates slower walking velocity (in both cases by >5%) and blue no change.















































7.5 Discussion

The purpose of this study was to examine the effects of rhythmic haptic cueing on spatial and temporal gait characteristics of people with hemiparesis.


Three kinds of improvement (amongst others) that physiotherapists and other relevant health professional seek to achieve in the gait of a hemiparetic stroke survivor are: better temporal asymmetry, longer stride length and higher walk velocity. Although, given the small number of participants, one must be careful in the interpretation of quantitative information, in terms of *mean* results both *during* and *immediately after* cueing, this is exactly what was observed.


Changes in *spatial* asymmetry will not be considered in more detail here, as the changes detailed earlier (section 7.4.4) were relatively slight.


However, a more nuanced, and arguably more interesting story unfolds when considering the results of individuals. Temporal and spatial results by individual for all participants are already presented separately in Figure 52 on page 141 (temporal); Figure 60 on page 150 (spatial), and Figure 63 on page 152 (velocity). In this section, the disparate results are integrated in Table 8 and Figure 64 below which summarises all results using colour coding to distinguish between improvements, declines and no change.


Participant code	Condition	
	<i>Cued</i>	<i>Post</i>
OUP01		
OUP02		
OUP03		
OUP04		
OUP05		
MMUP01	  	  
MMUP02	  	  
MMUP03	  	  
MMUP04	  	  
MMUP05	  	  
MMUP06	  	  


Key


 Temporal asymmetry

 Stride length (spatial)

 Velocity

 Improvement*

 No change*

 Decline*

*Compared to baseline

Table 8 Summary of spatiotemporal results

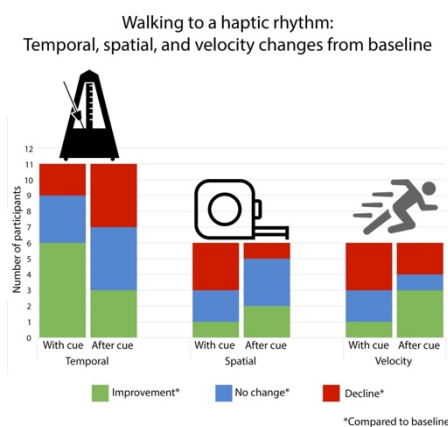


Figure 64 Mean temporal, spatial and velocity changes compared to baseline.

7.5.1 Temporal walk symmetry and temporal gait pattern

Six out of the eleven participants showed immediate improvements on their Overall Temporal Asymmetry (OTA) values. This indicates a more symmetric walking pattern, with the participants spending more time on their paretic leg, reducing the burden on the non-paretic leg. The wider implications of such a change are discussed in section 2.5.1, page 27. Two of these six participants retained good OTA value in the post condition, where they were asked to walk to the rhythm from memory. This suggests rhythm persistence and continuing entrainment influencing their motor response after the cue is removed. An analogous phenomenon has been noted in the past by (Thaut, 2007) (p.140) where hemiparetic patients were given an audio rhythmic stimulus for long periods of time, before asking them to walk to the rhythm from memory. The present study appears to be the first to show a similar persistence effect with a haptic cue and to demonstrate that this can take effect with relatively short exposure.

From the remaining four participants with improvements in the cued condition, one returned to their baseline symmetry, while the other three improved. Participants showed evidence in the post condition of becoming *more* asymmetric than their baseline. This increase in asymmetry may be attributable to fatigue, as the post condition was at the end of the study, after the participants had already walked roughly 120m (2x6x10m). While such a distance may not tax an able-bodied person, it can be considerably taxing for hemiparetics. Two participants commented explicitly that this was the longest they had walked since their stroke, and a third had to withdraw (see section 7.4.1, page 133) due to tiredness. Fatigue may have depressed the performance of other participants in the post condition without bringing it below baseline.

To conclude the discussion of temporal asymmetry, three participants (MMUP02, OUP02 and OUP04 – see Figure 52, page 141) showed no change in either the cued or post conditions. This may be either because they did not

understand or engage with the task or simply because they had far less room for improvement than other participants - these three participants had a relatively good OTA value in the baseline condition (1.08, 1.14, and 0.79 - normative range 0.9-1.1). However, one of these three participants (MMUP02) showed improvement in both *step lengths* and *velocity values* for both conditions, compared to her baseline. This indicates the possibility of therapeutic gait related benefits, even without change in temporal gait pattern. Unfortunately, no spatial or velocity data were collected for the other two participants (OUP02 and OUP04).

7.5.2 *Stride lengths and velocity changes*

In this study, only one out of the six participants both showed an immediate improvement in stride length, and maintained it during the post condition. MMUP02 who, normally uses a walking stick to ambulate, requested to do the trials without her stick, despite the protest of one of the physiotherapists present. When asked immediately after the trials, MMUP02 commented: “[...] *it’s when I’ve gone outside [my house] I’ve got no confidence, so I have the walking stick. [...] I felt a lot stronger walking in there without the stick. It made a difference in that I had a bit more confidence. I felt confident without the stick*”. When asked if this confidence was coming from the physiotherapists team present in the room she initially agreed, but then suggested further reasons: “*Yes I felt confident when she [physiotherapist] was there [next to her] but when she wasn’t there I still felt that confidence*”.

During the trials, Mrs Donaldson, the clinical gait analyst attending the study, also commented on how the posture of this participant changed from being crouched over her walking stick to walking upright, looking ahead. “[...] *look how tall she [MMUP02] stands*”. Interestingly, MMUP02 is one of the participants that showed *no* change in her temporal data. This outcome is not entirely surprising as there is evidence in the literature to suggest that spatial

and temporal parameters need not be directly related (Krasovsky and Levin, 2009).

Mrs Cannings, one of the expert physiotherapists collaborating in this research, subsequently remarked that OUP02 (one of the participants, who is also one of her regular physiotherapy patients) changed her habits after this study to include more walks in empty supermarket corridors during early mornings, when it is less busy. “[OUP02] *became more confident*” and “*started using a lighter walking stick*” which was interpreted by the therapist as another sign of increased confidence in her capabilities. While watching a video of OUP02 walking in one of the ‘with cue’ trials, Mrs Cannings commented that: “*It’s so nice to see her [OUP02] not thinking too much about her right (paretic) leg. Just let it go; let it flow*”.

This apparent gradual increase in confidence with increased familiarity with the environment and the procedure of the study can also be observed in the velocity changes between conditions. Velocity showed similar changes to stride length during cueing, with some participants getting worse/slower and some better/faster, with a similar pattern carrying on in the post condition.

After discussing the above findings with the physiotherapists assisting with the study, an interesting link between mood and one particular spatial (as opposed to temporal) gait characteristic was highlighted with a potential bearing on the above results. Physiotherapists and gait rehabilitation experts routinely expect a confident mood to be associated with long strides, whereas in situations where hemiparetic walkers are insecure and being mindful of how they walk, shorter strides are expected. Note that this behaviour is typically observed independent of cadence (i.e. walking *tempo*).

Therefore, due to the specific link of confidence with stride lengths and walk velocity, the relatively short exposure to this novel approach to walking may have had a crucial role in the spatial changes observed.

Walking to a haptic rhythm mediated via a multi-limb metronome is unusual and not often encountered in everyday life. The novelty of this approach may have decreased the confidence of some participants, when they walked slower and with shorter stride lengths – as observed in the cued condition.

However, with increased familiarity to the procedure, and having removed the task of feeling the rhythm while walking, the confidence for most participants increased and walked faster, with longer stride lengths (compared to their baseline) in the post condition when they were asked to walk to the rhythm from memory.

7.6 Conclusions

This chapter has presented a detailed empirical study of gait rehabilitation using haptic entrainment.

The chapter preceding this one showed that people can entrain to a haptic rhythm and empirically identified a *workable range* for such entrainment.

An overall beneficial decrease in the hemiparetic participants' overall temporal asymmetry (OTA) values was found, indicating an *immediate* improvement and a more symmetric and healthy gait pattern for six out of the eleven participants.

Spatial data were gathered from six of the eleven participants using a motion capture system showing three out of the six participants walked slower and with shorter strides with the cue than during their baseline. These spatial changes may be linked with confidence during walk, with shorter strides indicating temporarily decreased confidence levels, or higher cognitive load. Temporal asymmetry remained improved during the post condition.

Chapter 8

Conclusions

This thesis has explored the role of rhythmic cues delivered via the haptic modality in the context of entrainment-based gait rehabilitation. In this final chapter, the original research question is first revisited, then the main conclusions and contributions of the research are summarised. Limitations are considered and possible directions for future work are outlined.

8.1 Research question

The research question of the thesis was as follows:

How can entrainment through rhythmic haptic cueing assist with gait rehabilitation of neurological conditions?

Answering this question involved four principal activities:

- the design and implementation of a prototype wearable system (Chapter 5);
- a formative study with people affected by neurological conditions and health professionals specialised in treating such conditions (Chapter 4);
- two empirical studies, respectively to:
 - define a workable range for sensorimotor entrainment to isochronous haptic rhythms (Chapter 6);

- investigate changes in spatiotemporal gait characteristics of stroke and brain injury survivors when walking to an isochronous haptic rhythm (Chapter 7).

One result of the formative study was that it was decided to focus principally on those with neurologically caused hemiparetic gait: in particular, stroke and brain injury survivors.

8.2 Contributions to knowledge

Given the great variability of stroke survivors and the limited number of available participants, there is no claim in this thesis of statistical evidence able to support a formal experimental result of improved gait.

However, taking into account this great variability of participants, and viewing the empirical gait investigation as a set of eleven case studies, more modest empirical claims can be made. At a case study level, improvements were seen in the temporal data of six out of eleven participants.

Thus, this thesis has contributed to technologically-mediated neurological gait rehabilitation as follows.

- Presented the first systematic exploration of the haptic sense as a sole source of rhythm aiming at motor synchronisation via entrainment in the context of gait rehabilitation.
- Shown that hemiparetic stroke and brain injury survivors are generally able to synchronise their steps to a haptically presented rhythm.
- Shown empirically that this approach was able to yield an immediate (though not necessarily lasting) improvement of temporal gait characteristics for a substantial proportion of hemiparetic participants.
- Shown empirically that improvements to spatiotemporal gait characteristics can occur immediately subsequent to haptic cueing.

- Presented evidence of the persistence in short term memory of haptically presented rhythms.
- Presented the haptic tap test as a screening procedure for those with neurological conditions to distinguish between those who have physical difficulty walking to a rhythm, versus participants who are unable to entrain to a rhythm.

This thesis also contributed to the *knowledge of haptic entrainment* by:

- Identifying a workable range for motor entrainment to a haptically presented rhythm.

Additionally, contributions were made to the *interaction design for gait rehabilitation*. Specifically, this thesis identified:

- Design issues and design trade-offs, both for the design of physical prototypes and subsequent user studies. These involve: device placement (section 5.3.1, page 86, and 96); and the importance of involving *all* stakeholders *and* the technology in joint discussions (i.e. section 4.2).
- Unanticipated user preferences. In the technology probe study (section 4.2.5, page 66), participants rejected the idea of being given the ability to adjust the metronome tempo themselves and expressed a preference to leave this task to their carer. Furthermore, one participant in the early technology probe formative study (section 4.2) requested only one device on his paretic leg to overcome sensory and attention deficits.
- Tacit confluences of meanings and intentions between health practitioners of different medical fields. This highlights the importance of user studies involving all available stakeholders in order to discuss various aspects of the task at hand.

More generally, this thesis has contributed to entrainment-based haptic gait rehabilitation through the identification of a number of research issues as follows:

- The need for a better understanding of the interaction of entrainment, perception, sensory deficit, attention, memory, cognitive load and measurable gait characteristics in people with neurological conditions.
- The need for a better understanding of the bodily location of entrained haptic stimulation as it interacts with issues such as proprioception and cognitive load.
- The need for a better understanding of the interaction issues such as confidence and fatigue on gait.

Finally, the following *technological contributions* were made:

- A novel system with appropriate software was implemented to monitor and assess gait, avoiding the use of permanent room installations and semi-subjective measures.
- A multi-limb metronome, capable of delivering a steady, isochronous haptic rhythm to alternating legs, purpose-built for gait rehabilitation. This allows the systematic study of entrainment-based gait rehabilitation and the effects of attention and proprioception.

8.3 Limitations

8.3.1 Limitations in participant pool

The number of participants in this research was limited (eleven in the final study). In part, this represents the challenges of access to this community.

Due to safety considerations, participants were screened to be at least capable of independent community ambulation. This screening procedure may have affected the results in the final study, as discussed below.

8.3.2 *Medical record access*

Formal access to medical records was not available: medically relevant data was collected qualitatively directly from the participants. Consequently, it is possible that opportunities may have been missed to link, classify or predict results based on finely grained information of this kind.

8.3.3 *Procedure limitations*

Instructions

It was not always certain that some participants fully understood the task. Finding ways to improve the comprehension of instructions might alter the results.

Prototype wearable system used

The version of the Haptic Bracelet system used in this study was a functional prototype for running experiments, rather than a fully usability engineered system.

Wearing a wearable

Wearing the Haptic Bracelet, and, in the case of participants in Manchester, (see Chapter 7) the somewhat bulky optical markers (as well as being observed while wearing them) may have influenced the way participants walked.

Fatigue

There was some evidence that participants tended to continue without comment however tired they may have been feeling during this study - this may have affected their results in not easily identifiable ways.

8.4 Future work

8.4.1 Upper limb rehabilitation

This thesis presented the first systematic exploration of rhythmic haptic cueing in the context of gait rehabilitation. However, any rhythmic movement can in principle be entrained to an external rhythm. Rhythmic auditory stimulation (RAS) is already used for upper limb rehabilitation – currently almost exclusively in a research rather than clinical settings. With RAS, participants are asked to produce rhythmic movements in time to an auditory rhythm (typically musical). Rhythmic haptic cueing may have applications for upper limb rehabilitation.

8.4.2 Haptic rhythm persistence

Results from the study presented in Chapter 7 (post condition) indicate some short-term rhythm persistence in memory, and entrainment to the rhythm from memory. This is not the first time this phenomenon was observed, it is however the first time observed in the context of gait entrainment using haptically presented rhythms.

This thesis has presented evidence of persistence in short term memory of haptically presented rhythms. This rhythm persistence phenomenon may have significant implications for certain hemiparetic patients who suffer from attention deficits that make it challenging to perceive the rhythm and walk at the same time. This suggests a range of studies to investigate this phenomenon in more depth.

8.4.3 Longitudinal study with rhythmic haptic cueing

This thesis investigated the effects of rhythmic haptic cueing to the gait of hemiparetic stroke and brain injury survivors. This thesis has shown empirically that improvements to spatiotemporal gait characteristics can occur *immediately* subsequent to haptic cueing, leading to a more symmetric and healthy gait pattern for a substantial portion of participants. However, this was

a lab-based study, with hemiparetic participants receiving limited exposure to the haptic rhythm. The effects of longer exposure to a haptic rhythm for gait rehabilitation in a ‘home’ setting are currently unknown. A longitudinal study can be designed to investigate the effects of the haptic rhythm to hemiparetic patients’ gait over longer exposure times.

8.4.4 Continued iterative design

Given that the Haptic Bracelets system was a functional prototype system rather than a fully usability engineered system, it needs to be updated and moved from their current prototype state to a commercial state. This will include making the actual devices smaller and redesigning the straps making them more appropriate for the hemiparetic users.

8.4.5 Tool for physiotherapy

One of the contributions of this thesis to technologically-mediated neurological gait rehabilitation was the presentation of the haptic tap test as a screening procedure for those with neurological conditions. This system could be further developed to provide a tool for physiotherapists for gait assessment. Such a tool could be an addition or an alternative to the semi subjective tests currently used by physiotherapists (e.g. TUG and Rivermead mobility index test). The kinds of data produced by this approach also appear to have the potential to communicate progress in rehabilitation more clearly to patients.

8.4.6 Investigate wider neurological conditions

This thesis has shown empirically that rhythmic haptic cueing is able to yield an immediate improvement of temporal gait characteristics for a substantial proportion of hemiparetic participants; and more specifically survivors of stroke and brain injury incidents.

The approach of rhythmic haptic cueing can be extended to include other neurological conditions that lead to motor and gait deficits. Literature in rhythmic auditory stimulation (RAS - discussed in section 2.6.1) provides

evidence of the benefits of entrainment for neurological conditions such as Parkinson's disease, Cerebral Palsy and Huntington's disease. A similar approach to that followed in this thesis for hemiparetic stroke and brain injury survivors could be applied to investigate such conditions.

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Appendix 1 Collaboration agreement and ethics approvals

Collaboration agreement with P J Care

 **The Open University**

DATED _____ 2015

THIS AGREEMENT IS MADE ON X 2015

BETWEEN

1. **THE OPEN UNIVERSITY** a body incorporated by Royal Charter (number RC000391), an exempt charity in England and Wales, registered as a charity in Scotland (number SC038302) and with its address at Watton Hall, Milton Keynes, MK7, 6AA, Buckinghamshire, United Kingdom (OU); and

2. **P J CARE LTD** of 1 Sherwood Place 153 Sherwood Drive Bleichley Milton Keynes MK3 6RT ("PJC"),

(each a "party" and together referred to as the "parties").

1 DEFINITIONS AND INTERPRETATION

In this Agreement the following definitions apply:

"Agreement" this written agreement and the background;

"Commencement Date" the date of this Agreement;

"Confidential Information" the terms of this Agreement along with any and all information or materials in any form or medium (whether written, oral, visual or electronic) disclosed directly or indirectly by either party or its employees or representatives to the other in connection with this Agreement or the Previous Agreement which is of a confidential or proprietary nature or is received in circumstances in which the receiving party knows or should know that the information is confidential including without limitation any financial and commercial information relating to the business of either party;

"Excluded Information" information which:

(i) is or becomes part of the public domain through no direct or indirect act or default on the part of the parties;

(ii) was in the receiving party's lawful possession prior to disclosure and had not been obtained by the receiving party either directly or indirectly from

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	<p>the disclosing party;</p> <p>(iii) is lawfully disclosed to the receiving party by a third party without restriction on disclosure;</p> <p>(iv) is independently developed by the disclosing party's Confidential Information; or</p> <p>(v) is required to be disclosed by law or a court of competent jurisdiction or any competent judicial, governmental or regulatory body provided that prompt written notice of this requirement is given to the other party and such disclosure shall be only to the minimum extent required;</p>	<p>"Intellectual Property Rights"</p> <p>Intellectual property rights of any nature whatsoever, including without limitation copyright, know-how, technical and commercial information, design (whether registered or unregistered), design rights, internet domain names, database rights, trade marks, service marks or business names, applications to register any of the aforementioned rights, trade secrets and rights of confidence, in each case in any part of the world and whether or not registered or registrable;</p>	<p>"Materials"</p> <p>any and all works of authorship and materials developed, written or prepared by either party, its employees, agents or sub-contractors and arising out of the Alliance (Whether individually, collectively or jointly with the other party and on whatever media) including, without limitation, any and all publicity material, website content, reports, studies, data, charts, specifications, pre-contractual and contractual documents and all drafts thereof and working papers relating thereto, but excluding ordinary correspondence passing between PJC and the OU;</p> <p>materials contributed to the Alliance by the OU and not including, for the avoidance of</p>	<p>"OU Materials"</p> <p>materials contributed to the Alliance by the PJC and not including, for the avoidance of doubt, PJC's name or logo;</p> <p>"PJC Materials"</p>
				<p>doubt, the OU's name or logo;</p>
				<p>materials contributed to the Alliance by the PJC and not including, for the avoidance of doubt, PJC's name or logo;</p>
				<p>"PJC Materials"</p>
	<p>2 DURATION</p>			
	<p>2.1 This Agreement shall continue for 24 months unless it is terminated earlier by either party giving at least six months notice to the other or in accordance with clause 12. For the avoidance of doubt, such notice may be given by either party as of right, and need not be connected to the outcome of any review.</p>			
	<p>2.2 The Parties will review the ways of working and the extent to which the objectives of the Agreement are being met every six months as part of regular business meetings.</p>			
	<p>3 SCOPE AND VISION</p>			
		<p>3.1 The vision for the ongoing Alliance will be:</p>		
		<p>to investigate and evaluate haptic cueing for rehabilitation for a range of neurological conditions;</p>		
		<p>and the parties shall work together to seek to meet the aims of that vision.</p>		
		<p>3.2 The parties' focus for the term of this Agreement is to enable OU Staff to visit Eagle Wood, a PJC Care Home in Peterborough to carry out observation, dialogue, participative demonstrations and trials with staff and residents at Eagle Wood. The principal visitors from the OU will be Theodoros Georgiou, Dr Simon Holland, Dr Janet van der Linden and Dr Caroline Holland. At times, other researchers associated with the Haptic Bracelets Project may be involved.</p>		
			<p>3.3 Visits will always be by arrangement with PJC Care Staff. The frequency of visits may vary as the research progresses, but OU expects visits to be roughly fortnightly.</p>	
			<p>3.4 Activities at Eagle Wood will be assisted and advised by PJC Care staff and specialists.</p>	
			<p>3.5 Trials will help the OU research team to find out how haptic cueing can best be used for gait rehabilitation, and to evaluate the effects in a range of cases.</p>	
			<p>3.6 In some cases, for example brain trauma, it may be useful to explore rehabilitation of arms and legs using haptic cueing. This will guide the OU in the iterative modification of hardware and software, and OU understanding of how it can be most effectively applied.</p>	
				<p>3.7 A select number of residents may be taken to a Capture Motion Facility in Worcester, to gain clinical evidence of the technology's effectiveness.</p>

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- 3.8 Video and still photography will be used during the project for documentation for research purposes. In the cases of participants who have explicitly consented, this may also be used to disseminate the results of the research, and for presenting to potential funders. We will blur faces, except where participants have consented to use without blurring.
- 4 RESPONSIBILITIES**
- 4.1 To the extent permitted by law and in accordance with the scope and vision of this project, both parties shall use reasonable endeavours to:
- 4.1.1 PJC will provide access, by consent, to staff and residents with a range of neurological conditions that affect gait, allowing for evaluation of this new approach to rehabilitation. This is likely to take place on an approximately fortnightly basis from December 2015 until around July 2016.
- 4.1.2 PJC will arrange transportation for patients to Worcester as required for occasional motion capture sessions.
- 4.1.3 PJC will provide access to support, input and advice from experienced and knowledgeable medical staff, including physiotherapists, nurses, consultant neurologists and neuropsychologists (e.g. associated leading medical staff at Addenbrooke's Hospital that work with PJC under a Service Level Agreement). This will be around 8 staff members.
- 4.1.4 PJC will provide access to patients who agree to be involved in a research video (for example for submission in December 2015 to the CHI Conference in spring 2016).
- 4.1.5 The OU will credit PJC in any research that includes reference to this work with PJ Care and its patients.
- 5 WAYS OF WORKING**
- 5.1 Each party shall perform its obligations under this Agreement with reasonable skill and care.
- 6 INTELLECTUAL PROPERTY RIGHTS**
- 6.1 For the avoidance of doubt all Background Intellectual Property used in connection with the Project shall remain the property of the Party introducing the same. No Party will make any representation or do any act which may be taken to indicate that it has any right, title or interest in or to the ownership or use of any of the Background Intellectual Property of the other parties except under the terms of this Collaboration Agreement. Each Party acknowledges and confirms that nothing contained in this Collaboration Agreement shall give it any right, title or interest in or to the Background Intellectual Property of the other Parties save as granted by this Collaboration Agreement. The Parties agree that any improvements or modifications to a Party's Background Intellectual Property arising from the Project

- which are not severable from that Background Intellectual Property will be deemed to form part of that Party's Background Intellectual Property.
- 6.2 The OU shall own the Arising Intellectual Property generated by its employees, students and/or agents under the Project.
- 6.3 Where any Arising Intellectual Property is created or generated by two or more Parties jointly and it is impossible to segregate each Party's intellectual contribution to the creation of the Arising Intellectual Property, the Arising Intellectual Property will be jointly owned by those Parties in equal shares. The owners may take such steps as they may decide from time to time, to register and maintain any protection for that Arising Intellectual Property, including filing and prosecuting patent applications for any Arising Intellectual Property, and taking any action in respect of any alleged or actual infringement of that Arising Intellectual Property. If one or more of the owners does not wish to take any such step or action, the other owner(s) may do so at their expense, and the owner not wishing to take such steps or action will provide, at the expense of the owner making the request, any assistance that is reasonably requested of it.
- 6.4 Any joint owner of any of the Arising Intellectual Property may commercially exploit the Arising Intellectual Property upon consultation and agreement with the other Parties. In such circumstances, the Party which commercially exploits the Arising Intellectual Property will pay the other Party/Parties a fee and reasonable royalty rate(s) on the value of any products or processes commercially exploited by it which incorporate any Arising Intellectual Property taking into consideration the respective financial and technical contributions of the Parties to the development of the Arising Intellectual Property, the expenses incurred in securing intellectual property protection thereof and the costs of its commercial exploitation and the proportionate value of the Arising Intellectual Property in any such product or process.
- 6.5 The OU is hereby granted an irrevocable, non-transferable, royalty-free right to use all Arising Intellectual Property generated in the course of the Project for academic and research purposes, including research involving projects funded by third parties.
- 7 DATA PROTECTION**
- 7.1 Each party shall take all necessary steps to ensure that data or information belonging to the other party which comes into its possession or control in the course of performing its obligations under this Agreement is protected in accordance with data protection legislation and in particular each party shall not:
- 7.1.1 use the data or information nor reproduce the data or information in whole or in part in any form except as may be required by this Agreement; or
- 7.1.2 disclose the data or information to any third party or persons not authorised by the other party to receive it, except with the prior written consent of that party; or

- 7.1.3 alter, delete, add to or otherwise interfere with the data or information (save where expressly required to do so by the terms of this Agreement).
- 7.2 To the extent that any data or information belonging to each party is personal data within the meaning of the Data Protection Act 1998 ("Act"), each party warrants that it will:
- 7.2.1 process such data and information only in accordance with the other party's instructions;
- 7.2.2 not transmit such data and information to a country or territory outside the European Economic Area without the other party's express consent; and
- 7.2.3 take such technical or organisational measures against unauthorised or unlawful processing of such data and information and against accidental loss or destruction of, or damage to, such data and information as are appropriate to the other party's as data controller.
- 7.3 Each party will indemnify the other party against all breaches of the Act and the provisions of Clauses 9.1 and 9.2 in respect of the other party's data and information.
- 8 CONFIDENTIALITY**
- 8.1 Save as otherwise agreed between the parties in writing (including, without limitation, under the provisions of any previous non-disclosure agreement entered into between the parties), each party shall:
- 8.1.1 keep secret and confidential and procure to be kept secret and confidential all Confidential Information disclosed or obtained as a result of the relationship of the parties under this Agreement including the discussions leading up to and the entering into and performance of this Agreement;
- 8.1.2 keep all Confidential Information secure and protected against theft, damage, loss or unauthorised access;
- 8.1.3 not use or disclose the Confidential Information in whole or part to any third party except:
- to those of its employees, officers, agents and sub-contractors required to know such Confidential Information for the purposes of their proper performance of this Agreement; or
 - to its auditors or such other third party having a right, duty or obligation to know such Confidential Information which disclosure shall only be made with the prior written consent of the disclosing party;
- 8.1.4 use the disclosing party's Confidential Information solely in connection with this Agreement and not for its own benefit or the benefit of any third party.
- 8.2 The provisions of clause 10.1 shall not apply to any Excluded Information.

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- 8.3 Each party hereby undertakes to make all relevant employees, officers, agents and sub-contractors aware of the confidential nature of the Confidential Information and the provisions of this clause 12 and without limitation to the foregoing to take all such steps as shall from time to time be necessary to ensure compliance by its employees, officers, agents and sub-contractors with the provisions of this clause 12, including if the disclosing party so requests, requiring such employees, officers, agents and sub-contractors to enter into a deed of covenant with the disclosing party in a form reasonably acceptable to the disclosing party containing obligations equivalent to those set out in this clause.
- 8.4 Each party shall promptly inform the other if it becomes aware of any breach of confidence by any person and shall give the other party all reasonable assistance in connection with any proceedings which the other party may institute against such person.
- 8.5 Neither party shall make any announcement or issue any publicity concerning this Agreement or any matter ancillary thereto without the prior written consent of the other.
- 8.6 The obligations under this clause 10 shall survive the variation, renewal, termination or expiration of this Agreement.
- 9 LIABILITY**
- 9.1 Neither party's liability for any of the following is excluded or limited by this Agreement (even if any other term of the Agreement would suggest otherwise):
- death or personal injury caused by that party's negligence or the negligence of its employees agents or sub-contractors; or
 - any other liability which cannot be legally excluded or limited.
- 9.2 Subject to this clause neither party shall be liable under or in relation to this Agreement (whether such liability arises due to negligence, breach of contract, misrepresentation or otherwise) for any indirect or consequential loss or damage.
- 9.3 Subject to this clause and without prejudice:
- the OU's liability arising from or in connection with this Agreement (whether the liability arises for breach of contract, negligence, or otherwise) shall be limited to £100 for any single event or series of related events; and
 - PJC's liability arising from or in connection with this Agreement (whether that liability arises for breach of contract, negligence, or otherwise) shall be limited to £100 for any single event or series of related events.
- 9.4 The provisions of this clause shall survive the termination or expiry of this Agreement for any reason.

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10 TERMINATION

10.1 Without prejudice to any other rights to which it may be entitled, either party may immediately terminate this Agreement by written notice if the other party:

- 10.1.1 ceases or threatens to cease to carry on business; or
- 10.1.2 commits a material breach of any of the terms of this Agreement and (if such breach is remediable) fails to remedy that breach within 20 days of receiving written notice requiring it to do so; or
- 10.1.3 enters into liquidation (whether voluntary or compulsory) except a solvent voluntary liquidation for the purpose only of reconstruction or amalgamation, or has a receiver and/or manager, administrator or administrative receiver appointed of its undertaking or any part thereof, or a resolution is passed or a petition presented to any court for the winding up of the other party or any steps are taken (including, without limitation, the making of an application or the giving of any notice) for the appointment of an administrator in respect of the other party, or any proceedings are commenced relating to the insolvency or possible insolvency of the other party or if the other party takes or suffers any similar or analogous action in consequence of debt.
- 10.2 Save as expressly stated elsewhere in this Agreement, any termination of this Agreement (howsoever occasioned) shall not affect any accrued rights or liabilities of either party nor shall it affect the coming into force or the continuance in force of any provision which is expressly or by implication intended to come into force or continue in force on or after that termination.
- 10.3 On termination of this Agreement each party shall return to the other any property of the other party that it then has in its possession or control including without limitation any Confidential Information belonging to the other party.

11 FREEDOM OF INFORMATION

- 11.1 The OU is subject to the requirements of the Freedom of Information Act 2000 ("FOIA") and the Codes of Practice issued under the FOIA and the PJC shall assist and co-operate with the OU to enable it to comply with the requirements of the FOIA.
- 11.2 PJC agrees that:
 - 11.2.1 the decision on whether any exemption applies to a request for disclosure of recorded information under the FOIA is a decision solely for the OU; and
 - 11.2.2 where the OU determines that it is likely to disclose Confidential Information belonging to the PJC, the OU shall use its reasonable endeavours to notify the PJC in writing prior to such disclosure.

12 GENERAL

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Assignment and Sub-Contracting

12.1 Neither party may transfer, assign, charge or deal in any other manner with this Agreement or any or all of its rights hereunder nor purport to do any of the same, nor sub-contract any or all of its obligations under this Agreement, without the prior written consent of the other, such consent not to be unreasonably withheld or delayed.

Notices

12.2 Any notice given under this Agreement shall be in writing and shall be served by delivering it personally or sending it by pre-paid recorded delivery or registered post or subject to the provisions of clause 14.4 by e-mail to the address and for the attention of the relevant party set out in clause 14.5 (or as otherwise notified by that party hereunder). Any such notice shall be deemed to have been received:

- 12.2.1 if delivered personally, at the time of delivery; and
- 12.2.2 in the case of pre-paid recorded delivery or registered post, 48 hours from the date of posting.
- 12.3 In proving service of a notice under this Agreement it shall be sufficient to prove that the envelope containing such notice was addressed to the address of the relevant party set out in clause 14.5 (or as otherwise notified by that party hereunder) and delivered either to that address or into the custody of the postal authorities as a pre-paid recorded delivery or registered post letter.
- 12.4 A communication sent by e-mail shall not be effective unless the addressee acknowledges receipt of such communication, such acknowledgement to take the form of a return receipt. Any notice given by e-mail shall be deemed to have been duly given when the recipient of the said return receipt is able to access it.
- 12.5 The addresses and e-mail addresses of the parties for the purposes of this clause are:

The Open University
Ms Joanne Vango
Commercial Legal Services Manager
Finance Division
at the address specified in the preamble to this Agreement
Email: finance-comm-legal@open.ac.uk
FAX: 01908-858226

P J Care Ltd
Address: 1 Sherwood Place 153 Sherwood Drive Blechley Milton Keynes MK3 6RT

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For the attention of: Mrs Janice Flawn
E-mail address: Jan.Flawn@PJCare.co.uk
or such other address or e-mail address in the United Kingdom as may be notified in writing from time to time by the relevant party to the other party.

Relationship

12.6 Nothing in this Agreement is intended to or shall operate to create a joint venture of any kind between the parties or to authorise either party to act as agent for the other, and neither party shall have authority to act in the name or on behalf of or otherwise to bind the other in any way (including but not limited to the making of any representation or warranty, the assumption of any obligation or liability and the exercise of any right or power).

Waiver

12.7 The failure to exercise wholly or partially or delay in exercising a right or remedy provided by this Agreement or by law does not constitute a waiver of the right or remedy or a waiver of other rights or remedies. A waiver of a breach of any of the terms of this Agreement or of a default under this Agreement does not constitute a waiver of any continuing breach or of any other breach or default and shall not affect the other terms of this Agreement. A waiver of a breach of any of the terms of this Agreement or of a default under this Agreement will not prevent a party from subsequently requiring compliance with the waived obligation. The rights and remedies provided by this Agreement are cumulative and (subject as otherwise provided in this Agreement) are not exclusive of any rights or remedies provided by law.

Entire Agreement

12.8 This Agreement constitutes the entire agreement and understanding of the parties and, subject to the above, supersedes any previous agreement between the parties relating to the subject matter of this Agreement.

12.9 Each of the parties acknowledges and agrees that in entering into this Agreement, it does not rely on, and shall have no remedy in respect of, any statement, representation, warranty or understanding (whether negligently or innocently made) of any person (whether party to this Agreement or not) other than as expressly set out in this Agreement. Nothing in this clause shall, however, operate to limit or exclude any liability for fraud.

Third Party Rights

12.10 No terms of this Agreement shall be enforceable under the Contracts (Rights of Third Parties) Act 1999 by a third party.

Governing Law and Jurisdiction

12.11 This Agreement is governed by, and shall be construed in accordance with English law and each party agrees to submit to the exclusive jurisdiction of the English courts over any claim or matter arising under or in connection with this Agreement.

Use of OU logo or Brand Identity

12.12 In the event that P J Care wishes to use any of the University's logos or branding devices, then it confirms that it will:

- 12.12.1 Seek approval from the OU before using any of its branding material and
- 12.12.2 Conform to and comply with the Guidelines set out at <http://www.open.ac.uk/about/brand/> and
- 12.12.3 Submit any proposed use of branding material to the OU for approval prior to its use

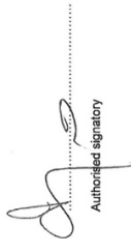
IN WITNESS of which the parties have signed this Agreement on the date stated at the beginning of this Agreement

SIGNED by

Joanne Vango

Commercial Legal Services
Manager

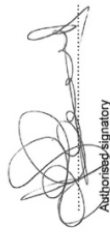
Authorised for and on behalf of
THE OPEN UNIVERSITY




Mrs Jan Flawn

Position

Duly authorised for and on
behalf of P J Care Ltd



Technology probe formative study.
(Chapter 4)



From Dr Duncan Banks
Chair, The Open University Human Research Ethics Committee
duncan.banks@open.ac.uk

Email 59198

To Theodoros Georgiou, Computing and Communications

Subject "Gait rehabilitation using haptic cues."

Ref HREC/2014/1861/Georgiou/1

AMS (RED) n/a

Submitted 25 November 2014

Date 1 December 2014


Memorandum

This memorandum is to confirm that the research protocol for the above-named research project, as submitted for ethics review, has been given a **favourable opinion** by the Open University Human Research Ethics Committee. Please note that the OU research ethics review procedures are fully compliant with the majority of grant awarding bodies and their Frameworks for Research Ethics.

Please make sure that any question(s) relating to your application and approval are sent to Research-REC-Review@open.ac.uk quoting the HREC reference number above. We will endeavour to respond as quickly as possible so that your research is not delayed in any way.

At the conclusion of your project, by the date that you stated in your application, the Committee would like to receive a summary report on the progress of this project, any ethical issues that have arisen and how they have been dealt with.

Regards,



Dr Duncan Banks
Chair OU HREC

The Open University is incorporated by Royal Charter (number FC 000391), an exempt charity in England & Wales and a charity registered in Scotland (number SC 038302)
HREC_2014-1861-Georgiou-1 approval

MANCHESTER METROPOLITAN UNIVERSITY
FACULTY OF HEALTH, PSYCHOLOGY AND SOCIAL CARE

M E M O R A N D U M

FACULTY ACADEMIC ETHICS COMMITTEE



Manchester Metropolitan University

To: Prof Josie Tetley

From: Prof Carol Haigh

Date: 27/11/2014

Subject: Ethics Application 1263

Title: Can haptic bracelets improve gait after stroke? A proof of concept study

Thank you for your application for ethical approval.

The Faculty Academic Ethics Committee review process has recommended approval of your ethics application. This approval is granted for 42 months for full-time students or staff and 60 months for part-time students. Extensions to the approval period can be requested.

If your research changes you might need to seek ethical approval for the amendments. Please request an amendment form.

We wish you every success with your project.

Prof Carol Haigh and Prof Joie Stansfield
Chair and Deputy Chair
Faculty Academic Ethics Committee

Haptic rhythm perception - The haptic tap test. (Chapter 6)



From Dr Duncan Banks
Chair, The Open University Human Research Ethics Committee
Email duncan.banks@open.ac.uk
Extension 59198

To Theodoros Georgiou, Computing and Communications

Subject *"Synchronising to a haptic rhythm when an audio distraction is introduced."*

Ref HREC/2015/2088/Georgiou/1

AMS (Red)

Submitted 08 September 2015

Date 08 September 2015

Memorandum

This memorandum is to confirm that the research protocol for the above-named research project, as submitted for ethics review, **has been given a favourable opinion** by the Open University Human Research Ethics Committee by **Chair's action** as it is thought to be low risk. Please note that the OU research ethics review procedures are fully compliant with the majority of grant awarding bodies and their Frameworks for Research Ethics.

Please make sure that any question(s) relating to your application and approval are sent to Research-REC-Review@open.ac.uk quoting the HREC reference number above. We will endeavour to respond as quickly as possible so that your research is not delayed in any way.

At the conclusion of your project, by the date that you stated in your application, the Committee would like to receive a summary report on the progress of this project, any ethical issues that have arisen and how they have been dealt with.

Regards,

Dr Duncan Banks
Deputy Chair OU HREC

Rhythmic haptic cueing for gait rehabilitation.
(Chapter 7)



Human Research Ethics Committee (HREC)

From: Marc Cornock, Deputy Chair
The Open University Human Research Ethics Committee
Email: marc.cornock@open.ac.uk
(6) 55807
To: Theodoros Georgiou
Project title: Rhythmic haptic cueing for walking after hemiparetic stroke

HREC ref: HREC/2015/2088/Georgiou/1
AMS ref: 240773

Date application submitted: 15/08/16
Date of HREC response: 13/10/17

Memorandum

This memorandum is to confirm that the research protocol and the additional information provided the above-named research project, as submitted for ethics review, has been given a favourable opinion by the Open University Human Research Ethics Committee.

Please note the following:

1. You are responsible for notifying the HREC immediately of any information received by you, or of which you become aware which would cast doubt on, or alter, any information contained in the original application, which would raise questions about the safety and/or continued conduct of the research.
2. It is essential that any proposed amendments to the research are sent to the HREC for review, so they can be recorded and a favourable opinion given prior to any changes being implemented (except only in cases of emergency when the welfare of the participant or researcher is or may be affected).
3. Please make sure that any question(s) relating to your application and approval are sent to Research-REC-Review@open.ac.uk quoting the HREC reference number above. We will endeavour to respond as quickly as possible so that your research is not delayed in any way.
4. OU research ethics review procedures are fully compliant with the majority of grant awarding bodies and where they exist, their Frameworks for Research Ethics.
5. At the conclusion of your project, by the date that you stated in your application, the Committee would like to receive a summary report on the progress of this project, any ethical issues that have arisen and how they have been dealt with.

Kind regards,

Dr Marc Cornock, Deputy Chair

The Open University Human Research Ethics Committee

<http://www.open.ac.uk/research/ethics/>

www.open.ac.uk/research/ethics/

MANCHESTER METROPOLITAN UNIVERSITY
FACULTY OF HEALTH, PSYCHOLOGY AND SOCIAL CARE

M E M O R A N D U M

FACULTY ACADEMIC ETHICS COMMITTEE



Manchester
Metropolitan
University

To: Prof Josie Tetley

From: Prof Carol Haigh

Date: 11/10/2016

Subject: Ethics Checklist 1368

Title: Developing a wearable prototype to improve the walking of stroke survivors

Thank you for your application for an amendment to your original ethical approval.

The Faculty Academic Ethics Committee review process has recommended approval of your amendment. This approval is granted for 42 months for full-time students or staff and 60 months for part-time students. Extensions to the approval period can be requested.

If your research changes you might need to seek ethical approval for the amendments. Please request an amendment form.

We wish you every success with your project.

Prof Carol Haigh and Prof Jois Stansfield
Chair and Deputy Chair
Faculty Academic Ethics Committee

Appendix 2

Rivermead mobility index

The main purpose of the Rivermead Mobility Index (RMI) is to quantify mobility disability in patients with stroke, spinal cord injury, and acquired brain injury. The RMI is clinically relevant in testing functional abilities such as gait, balance, and transfers.

It consists of fourteen self-reported and one direct observation item. The items in the test progress in difficulty and are coded as either 0 or 1, depending on whether the patient can complete the task according to specific instructions. The score of 0 is given for a "No" response and 1 for a "Yes" response. A maximum of 15 points is possible. Intuitively, higher scores indicate better mobility performance. A score of "0" indicates an inability to perform any of the activities on the measure.

An example RMI test sheet can be found on the next page.

The Rivermead Mobility Index

Name: _____

Day							
Month							
Year							
Topic and Question:							
Turning over in bed: Do you turn over from your back to your side without help?							
Lying to sitting: From lying in bed, do you get up to sit on the edge of the bed on your own?							
Sitting balance: Do you sit on the edge of the bed without holding on for 10 seconds?							
Sitting to standing: Do you stand up from any chair in less than 15 seconds and stand there for 15 seconds, using hands and/or an aid if necessary?							
Standing unsupported: (Ask to stand) Observe standing for 10 seconds without any aid							
Transfer: Do you manage to move from bed to chair and back without any help?							
Walking inside: (with an aid if necessary): Do you walk 10 meters, with an aid if necessary, but with no standby help?							
Stairs: Do you manage a flight of stairs without help?							
Walking outside: (even ground): Do you walk around outside, on pavements, without help?							
Walking inside: (with no aid): Do you walk 10 meters inside, with no caliper, splint, or other aid (including furniture or walls) without help?							
Picking up off floor: Do you manage to walk five meters, pick something up from the floor, and then walk back without help?							
Walking outside: (uneven ground): Do you walk over uneven ground (grass, gravel, snow, ice etc) without help?							
Bathing: Do you get into/out of a bath or shower and to wash yourself unsupervised and without help?							
Up and down four steps: Do you manage to go up and down four steps with no rail, but using an aid if necessary?							
Running: Do you run 10 meters without limping in four seconds (fast walk, not limping, is acceptable)?							
Total							

Downloaded from www.rehabmeasures.org

The Rivermead Mobility Index is provided courtesy of Dr. Derick Wade and the Oxford Centre for Enablement.

Appendix 3

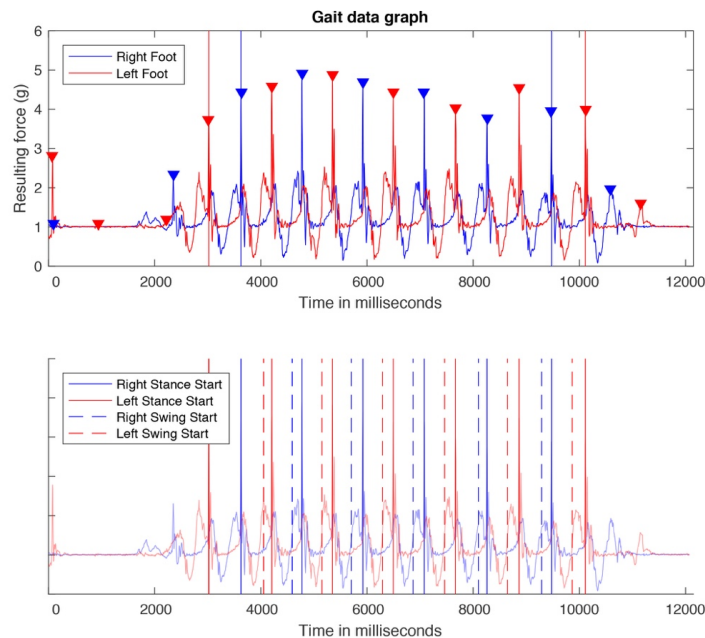
The Haptic Bracelets system gait analysis sample

The gait analysis software developed as part of the Haptic Bracelet system, can produce reports summarising a person's gait. The items of this report include exclusively temporal characteristics such as stride times (heel to heel strikes of the same leg), step times (heel to heel strikes of alternating legs), and stance and swing times for each leg. Graphs are also provided to help explain to physiotherapists and patients the meanings of the measures. The graphical representation of the data was greeted with positive comments by all physiotherapists involved in this research.

This Appendix presents two sample reports; one from a healthy adult, and one from a hemiparetic patient.

Healthy adult report

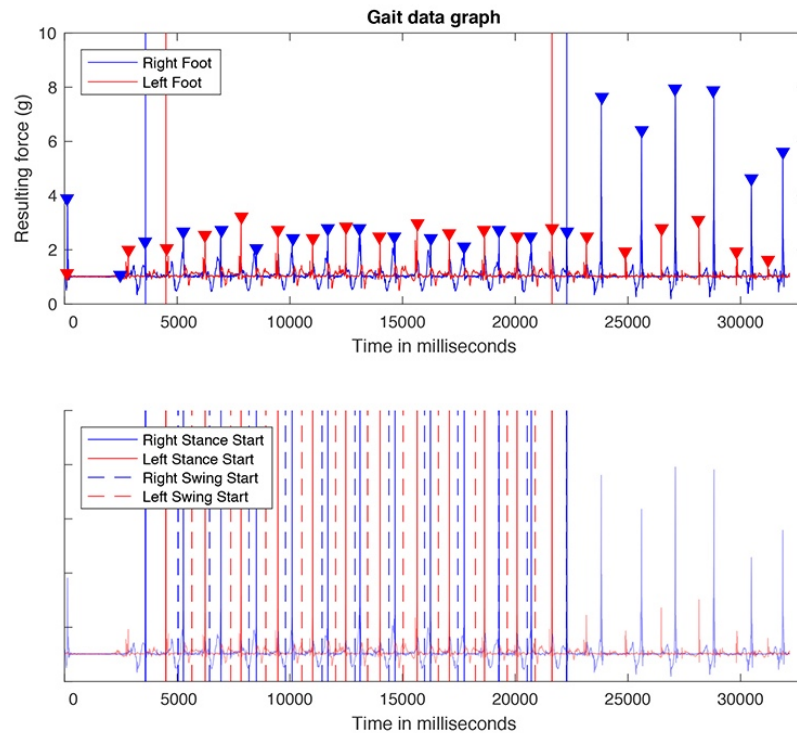
Sampling Rate	254.05Hz (254.14) - 248.02Hz (248.10)
Right leg cycle time	1170.20ms \pm 29.55
Left leg cycle time	1181.83ms \pm 39.21
Right step time	584.38ms \pm 13.53 (CV = 2.32%)
Left step time	584.62ms \pm 15.61 (CV = 2.67%)
Estimate walk period	588.01ms
Right Stance / Swing time	965.25ms \pm 39.92 193.26ms \pm 26.12
Left Stance / Swing time	974.00ms \pm 35.42 195.00ms \pm 23.33
OTA estimate	R: 1.00 L: 1.00



This report represent data from a healthy adult with no known gait deficiencies. Their OTA value indicates perfect symmetry (even though this is not always the case even for healthy people – normative range: 0.9-1.1).

Hemiparetic adult report

Sampling Rate	253.99Hz (254.02) - 254.13Hz (254.16)
Right leg cycle time	1557.75ms \pm 77.85
Left leg cycle time	1557.35ms \pm 93.75
Right step time	894.56ms \pm 62.53 (CV = 6.99%)
Left step time	661.71ms \pm 47.92 (CV = 7.24%)
Estimate walk period	778.78ms
Right Stance / Swing time	1297.17ms \pm 106.73 259.10ms \pm 116.02
Left Stance / Swing time	1056.48ms \pm 75.78 501.61ms \pm 71.29
OTA estimate	R: 0.42 L: 2.38

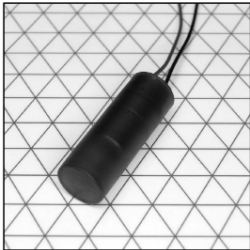


This report represent data from a 73-year-old hemiparetic stroke survivor (Left is their hemiparetic side). Their OTA value of 2.38 suggest severe asymmetry. The data also indicate this patient is spending more time standing on their right, non-paretic time than on their left (longer stance time). They are also swinging the non-paretic leg faster (swing time is almost half than the paretic), trying to get off the paretic leg as fast as possible. This asymmetric gait pattern may lead to health problems as discussed in Chapter 2, section 2.5.

Appendix 4

Vibrotactile actuator datasheet

307-100



9mm Vibration Motor - 25mm Type
Shown on 6mm Isometric Grid



Product Data Sheet
Pico Vibe™
9mm Vibration Motor - 25mm Type

Model: 307-100

Ordering Information

The model number 307-100 fully defines the model, variant and additional features of the product. Please quote this number when ordering.
For stocked types, testing and evaluation samples can be ordered directly through our online store.

Datasheet Versions

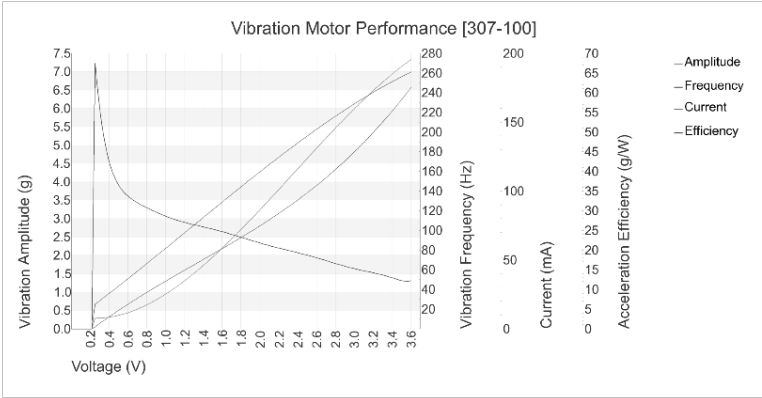
It is our intention to provide our customers with the best information available to ensure the successful integration between our products and your application. Therefore, our publications will be updated and enhanced as improvements to the data and product updates are introduced.
To obtain the most up-to-date version of this datasheet, please visit our website at: www.precisionmicrodrives.com
The version number of this datasheet can be found on the bottom left hand corner of any page of the datasheet and is referenced with an ascending R-number (e.g. R002 is newer than R001). Please contact us if you require a copy of the engineering change notice between revisions.

If you have any questions, suggestions or comments regarding this publication or need technical assistance, please contact us via email at: enquiries@precisionmicrodrives.com or call us on +44 (0) 1932 252 482

Key Features

Body Diameter:	8.8 mm [+/- 0.2]
Body Length:	24.9 mm [+/- 0.3]
Rated Operating Voltage:	3 V
Rated Vibration Speed:	13,500 rpm [+/- 2,700]
Typical Rated Operating Current:	130 mA
Typical Normalised Amplitude:	6 G

Typical Vibration Motor Performance Characteristics



307-100

Physical Specification

PARAMETER	CONDITIONS	SPECIFICATION
Body Diameter	Max body diameter or max face dimension where non-circular	8.8 mm [+/- 0.2]
Body Length	Excl. shafts, leads and terminals	24.9 mm [+/- 0.3]
Unit Weight		4.6 g

Construction Specification

PARAMETER	CONDITIONS	SPECIFICATION
Motor Construction		Coreless
Commutation		Precious Metal Brush
No. of Poles		5

Leads & Connectors Specification

PARAMETER	CONDITIONS	SPECIFICATION
Lead Length	Lead lengths defined as total length or between motor and connector	47 mm [+/- 2]
Lead Strip Length		1.5 mm [+/- 0.5]
Lead Wire Gauge		30 AWG
Lead Configuration		Straight

Operational Specification

PARAMETER	CONDITIONS	SPECIFICATION
Rated Operating Voltage		3 V
Rated Vibration Speed	At rated voltage using the inertial test load	13,500 rpm [+/- 2,700]
Max. Rated Operating Current	At rated voltage using the inertial test load	250 mA
Rated Inertial Test Load	Mass of standard test sled	100 g
Min. Vibration Amplitude	Peak-to-peak value at rated voltage using the inertial test load	4.2 G
Max. Start Voltage	With the inertial test load	0.75 V
Max. Operating Voltage		3.6 V
Max. Start Current	At rated voltage	680 mA
Min. Insulation Resistance	At 50V DC between motor terminal and case	1 MOhm

Important: The characteristics of the motor is the typical operating parameters of the product. The data herein offers design guidance information only and supplied batches are validated for conformity against the specifications on the previous page.

Typical Performance Characteristics

PARAMETER	CONDITIONS	SPECIFICATION
Typical Rated Power Consumption	At rated voltage and load	390 mW
Typical Rated Operating Current	At rated voltage using the inertial test load	130 mA
Typical Vibration Amplitude	Peak-to-peak value at rated voltage using the inertial test load	6 G
Typical Start Current	At rated voltage	430 mA
Typical Vibration Efficiency	At rated voltage using the inertial test load	15.4 G/W
Typical Normalised Amplitude	Peak-to-peak vibration amplitude normalised by the inertial test load at rated voltage	6 G
Typical Start Voltage	With the inertial test load	0.25 V
Typical Terminal Resistance		5.5 Ohm
Typical Terminal Inductance		43 uH

Typical Haptic Characteristics

PARAMETER	CONDITIONS	SPECIFICATION
Typical Lag Time	At rated voltage using the inertial test load	6 ms
Typical Rise Time	At rated voltage using the inertial test load	22.5 ms
Typical Stop Time	At rated voltage using the inertial test load	56.5 ms
Typical Active Brake Time	Time taken from steady-state to 0.04 G under inverse polarity at max. voltage	19.3 ms

Typical Durability Characteristics

PARAMETER	CONDITIONS	SPECIFICATION
Typical Max. Mech. Noise		45 dB(A)

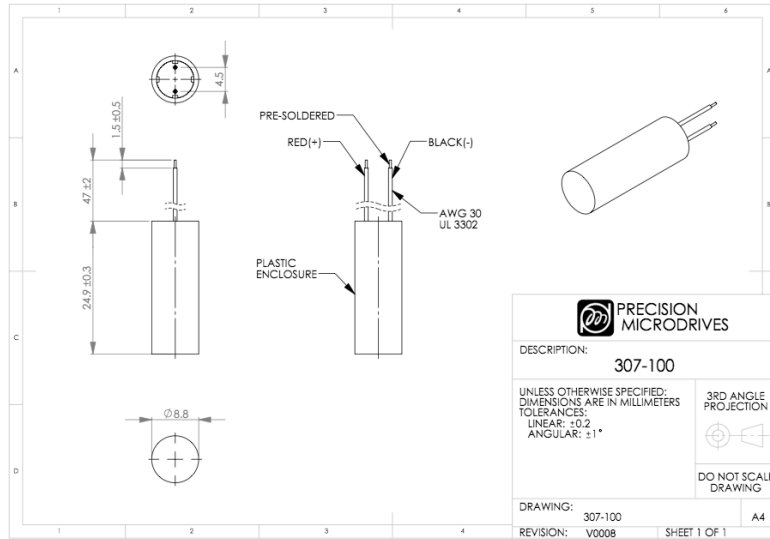
Environmental Characteristics

PARAMETER	CONDITIONS	SPECIFICATION
Min. Operating Temp.		-20 Deg.C
Max. Operating Temp.		60 Deg.C
Min. Storage Temp.		-30 Deg.C
Max. Storage Temp.		70 Deg.C

Typical Packing Conditions

PARAMETER	CONDITIONS	SPECIFICATION
Carton Type		Boxed Trays

307-100

Product Dimensional Specification**Life Support Policy**

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1. Life support devices or systems are devices or systems which, (a) are intended for surgical implant into the body, or (b) support or sustain life, and whose failure to perform when properly used in accordance with instructions for use provided in the labeling, can be reasonably expected to result in a significant injury to the user.
2. A critical component is any component of a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or system, or to affect its safety or effectiveness.



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