Rhythmic Haptic Cueing for Entrainment: Assisting Post-stroke Gait Rehabilitation

T. Georgiou, S. Holland and J. van der Linden

Abstract: Restoring mobility and rehabilitation of gait are high priorities for rehabilitation from neurological conditions. Cueing using metronomic rhythmic sensory stimulation via entrainment has been shown to improve gait, but almost all previous versions of this approach have used auditory or visual cues. In contrast, we have developed and pilot-tested a prototype wearable system for rhythmic cueing based on haptics. Our initial pilot study indicated the same kinds of improvement to gait with haptics as for other cueing modalities, but haptics offer some advantages over audio and visual cues. In particular, haptics are generally more practical for use out of doors, in noisy environments, or when wishing to keep open the ability to converse freely. However, haptics also allow the precisely targeted spatial placement of cues on alternate limbs, offering the ability to manipulate attention and proprioception for therapeutic benefit. We outline the theory behind our approach and report on the iterative design of the system as part of a user-centred design evaluation process involving a wide range of stakeholders.

1 Introduction

Stroke is a sudden and devastating disease with major implications to a person's health and quality of life. In contrast to other sudden diseases, such as heart disease, stroke has a long-term disability burden. The disability impact of stroke is greater than any other chronic disease, causing a wider range of complex disabilities (including locomotion, dexterity, and communication related disabilities), making stroke a leading cause of adult disability (Adamson et al. 2004). More than half of all stroke survivors are left dependent on others for everyday activities (Intercollegiate Stroke Working Party 2012).

After acute specialist hospital care, a person's recovery can significantly improve with regular rehabilitation exercises both in the early days after a stroke and long after they return home (Galvin et al. 2009). Indeed, even rehabilitation carried out

T. Georgiou (✉) · S. Holland · J. van der Linden
Centre for Research in Computing, The Open University, Milton Keynes, UK
e-mail: Theodoros.Georgiou@open.ac.uk

years after a stroke can still lead to improvements. However, effective rehabilitation outside a clinical setting and without guidance can be difficult to achieve.

New wearable technologies offer the possibility of small, light inconspicuous devices, which are capable of supporting day-to-day rehabilitation exercises through appropriate guidance and monitoring. However, there are serious challenges involved in the design of such systems. Wearable healthcare systems need to take into account the physical, sensory and cognitive abilities of intended users. Addressing these problems involves user-centred design approaches, including the designing of functional prototypes that users can engage with in depth.

Prototypes help designers to understand diverse real world issues and to identify and evaluate potential improvements. They enable participants to physically explore the possibilities of new technologies, and provide a source of inspiration for future use scenarios.

In this paper we describe our approach of assisting gait rehabilitation by providing rhythmic haptic (i.e. touch-based) cues through a technology known as the *Haptic Bracelets*. The Haptic Bracelets (discussed in detail below) were originally developed (and still are used) to support the development of musical skills in learning multi-limbed rhythms (Holland et al. 2010, Bouwer et al. 2013). They were subsequently adapted for gait rehabilitation using haptic cues, drawing on the established use of rhythmic audio and visual cues for gait rehabilitation using entrainment, as outlined below.

The Haptic Bracelets are light wearable and wireless devices, designed to work in pairs, one strapped on each leg at ankle height. The devices are capable of monitoring several aspects of the wearer's gait in high resolution and provide rhythmic haptic cues through an array of vibrotactile motors. The person wearing them is instructed to feel the haptic cues and try to time their steps to that rhythm.

Before detailing the design and implementation of the Haptic Bracelets, it is useful to consider the mechanisms underlying the human ability to sense and follow a rhythm or rhythmic pattern.

2 Rhythmic Cueing for Entrainment (RCE)

The mechanisms by which an external rhythmic stimulus can affect and improve a persons gait may not be immediately obvious. The mechanism is neither stimulus response nor direct muscle stimulus, but rather biological *entrainment*.

To understand the difference, consider everyday applications of vibrotactiles, which typically focus on notifications and alerts. Applications of this kind are best understood in terms of stimulus response. When, for example, a smartphone in silent mode vibrates to give an alert, there is a necessary delay in perception while the sensory stimulus is processed, and then a further delay while any resulting human action is enacted. Broadly, this process is one of stimulus and response (though variants can involve cognitively learned responses, conditioned responses, or direct muscle responses).

Therefore, responses to notifications and alerts always involve delays. By contrast, after hearing a few initial beats, most people can generally tap along to a regular pulse in more or less exact synchronisation. This is a special case of biological entrainment.

Entrainment is a physical phenomenon whereby two rhythmic processes interact with each other until they adjust to a common (or closely related) rhythm. The phenomenon was first identified in the fields of physics and mathematics, and is characterised by the effect that one harmonic oscillator has on the motion of a second nearby powered oscillator which is oscillating at a similar frequency. More specifically, entrainment is the process where two autonomous oscillating bodies, which have different periods when they function independently, assume a common or simply related period.

Instances of entrainment must adhere to two major rules (Clayton et al. 2005):

1. **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.
2. **There must be a link to allow the oscillations to interact**. A link must exist between the oscillators, which is weak enough so as not cause the oscillators to lose their individuality, but is strong enough to link the interaction between the oscillators.

It was only recently (early 1990s) that biological instantiations of entrainment were identified. The human body is full of naturally occurring rhythms, with the heart beating, respiration, and various perceptual processes being just few of them. These endogenous rhythms may very easily entrain to each other within a single person (e.g. the synchronisation of respiration and heart rhythm patterns of high performance swimmers (Schäfer et al. 1998)) or with external rhythms that fit the above characterisations (e.g. singers whose heartbeats entrain to the rhythm of the music they are singing (Vickhoff et al. 2013)).

Since the early nineties, the concept of entrainment has been explicitly applied to gait rehabilitation, as detailed below.
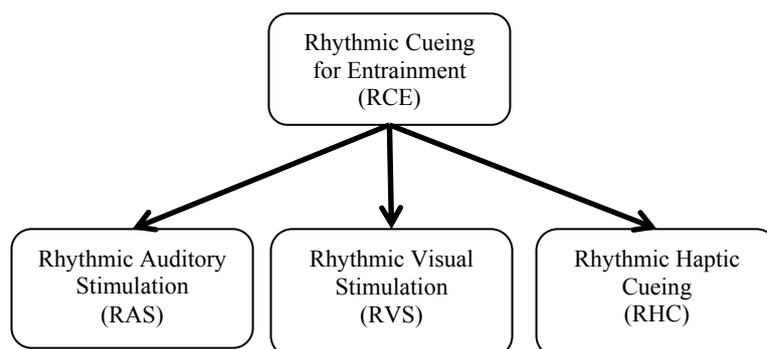
2.1 RCE for Gait Rehabilitation

Stroke survivors commonly experience what is known as hemiparetic gait where one side of the survivor's body is physically weakened. Hemiparetic gait is characterised variously by increased step length variability (Balasubramanian et al. 2009), and temporal and spatial gait asymmetry (Chen et al. 2005). Many health

problems are associated with this disorder, for example the non-paretic (stronger) limb may be exposed to higher vertical forces (Kim and Eng 2003) which can lead to joint pains (Norvell et al. 2005), degeneration (Nolan et al. 2003) and increased risk of fractures.

Entrainment can be used to help patients suffering from gait related disorders assume a more symmetrical walking rhythm (Thaut et al. 1993) via mechanisms that we will now explain.

The provision of an external rhythmic cue can assist the brain to control the movement of the leg swing in several different ways. Firstly, and most obviously the external rhythm gives a recurring reference for the period of the desired swing. Perhaps less obviously, it can also make the motion smoother, with less variability of movement trajectory and can lead to more even muscle recruitment (Thaut et al. 2015). These effects are caused by changes in muscle activation patterns, with the associated brain plasticity making it possible to re-program movement. Thus, the effect of the cue is to optimise diverse aspects of motor control via physiological period entrainment of the motor system (Thaut et al. 1999).

As already noted, different modalities can be used to deliver the rhythmic cues for entrainment: audio, visual and our proposal of haptic (summarised below).

Fig. 1 Different modalities for rhythmic cueing for entrainment

2.2 Existing Applications of Entrainment to Gait Rehabilitation

The idea of using metronomic cueing to support gait rehabilitation for people suffering from various neurological conditions has been explored by researchers using a variety of sensory channels, principally auditory and visual.

Rhythmic audio cueing (RAS) delivered through headphones has been shown to lead to gait improvements with immediate effects (Thaut et al. 2007). In some cases, these improvements may last beyond the immediate application of the cues (Benoit et al. 2014).

More specifically, studies with participants suffering from post-stroke gait impairments walking on a treadmill, and RAS providing the walking rhythm, show improvements in spatial (Prassas et al. 1997) and temporal symmetry

(Roerdink et al. 2007) as well as significant improvements in step time asymmetry and the step time variability (Wright et al. 2013).

Similar encouraging results were also observed during rhythmic *visual* stimulation (RVS) where cues were projected in front of participants walking on a treadmill as stepping stones, with increase in stride length being the most prominent one (Bank et al. 2011).

Rhythmic cueing is therefore a promising approach, but the use of audio or visual cueing modes can be problematic outside the controlled environment of a lab or a clinic. When outside a clinical setting, it is generally important to keep the audio channel clear. This allows one to remain aware of the environment, or to deal with traffic or just to hold conversations while walking. Approaches involving visual cues and projections in front of a user while walking typically require extensive laboratory installations, and in any case are highly distracting.

Haptics on the other hand leave sight and hearing unobstructed. This makes haptics particularly well suited for gait rehabilitation outside controlled environments such as labs and clinics. This opens up new ways in which stroke survivors can take charge of their own rehabilitation.

Evidence suggests that rehabilitation in the home environment can be more beneficial than in a clinical setting (Hillier and Inglis-Jassiem 2010). The approach of self-managed rehabilitation has the potential to offer substantial cost savings for health services, considering that the current stroke care provision plan in the UK is estimated to cost an average of £24,855 per patient (National Audit Office 2010).

3 Rhythmic Haptic Cueing for Entrainment

In an earlier pilot study where *rhythmic haptic cueing* (RHC) was used for providing walking rhythm to a participant through RHC entrainment (Holland et al. 2014), the participant's step length was found to increase, while a range of other measures such as the paretic (affected by stroke), hip angle at toe off, peak knee flexion during swing and ankle range of motion showed significant clinical improvement indicating improved gait movement and similar walking benefits to those of audio rhythm.

This approach of using RHC for entrainment in gait rehabilitation not only helps to overcome some of the practical limitations in audio and visual cueing approaches (e.g. intrusiveness and masking of the audio and visual channel) but may also have some interesting advantages, unique to the RHC approach. RHC, for example, has the ability to target specific limbs through different spatial placement, with the potential to manipulate attention and proprioception for therapeutic benefit.

In a qualitative user-centred study aimed at investigating the views of stroke survivors and health professionals (Georgiou et al. 2015), comments from both groups both were generally positive. More specifically, all four stroke survivors agreed that the haptic cue gave them "a rhythm to walk to".

4 Technology and Prototype Development for RHC

In this section we will consider the first three iterations in the design of the Haptic Bracelets (HBI, HBII and HBIII), the prototype wearable devices we are using to assist gait rehabilitation via RHC.

Even though the earlier version (HBI) could deliver high quality rhythmic haptic cue in a precise manner, leading to clinically positive results in pilot trials, hardware limitations meant that they could only gather a limited range of gait related data, and networking limitations meant that under certain conditions data could get corrupted. This motivated us to redesign the devices from the ground up, adding sensors with higher temporal resolution for gait monitoring and better networking protocols. During this process, the devices also got smaller, lighter and gained better battery life.

HBII measured 47x34x15mm, with a custom designed and 3D printed case enclosing all the electronic components. A vibrotactile actuator of 24.9mm length and 8.8mm diameter protrudes from it on a wire of variable length. These prototype devices (designed to work in pairs of two) can be seen on Figure 2.

Fig. 2 Last user-tested version of the Haptic Bracelets (left). A Haptic Bracelet device strapped on a user's leg (right).

Each HBII contain a complete Inertia Monitoring Unit (IMU). The IMU is made up of a six degrees of freedom accelerometer, gyroscope and magnetometer (i.e. all sensors can measure data in three axes) and can sample data at a maximum rate of 400Hz (400 times a second) before sending them to a central control unit.

All communications between the central control unit (i.e. laptop) and the Haptic Bracelets are sent over Wi-Fi using the Open Sound Control transport control protocol. Each HBII unit is uniquely identified in the network by their IP addresses, making it easy to analyse and log data coming from specific HBII units and to send targeted instructions (e.g. when and how intensely to vibrate). All time stamping on the data received is done on the central control unit to ensure

consistency, since temporal precision is important, and the local clocks on the two bracelets can drift slightly relative to each other.

The entire HBII wearable system is powered by two batteries of 3000mAh each, capable of providing a regulated 5V output. The batteries can be recharged using a standard micro-USB cable and a 5V, 1.2A charger (standard USB charger). Ease of charging is an important design goal in self-managed settings.

4.1 Participative Design Development and Evaluation

While the initial pilot study (Holland et al. 2014) raised some interesting questions regarding the design and placement of the devices from the participant's point of view, more in-depth dialogue with potential users and other major stakeholders of the system, such as physiotherapists, clinicians and health professionals was desired.

For the qualitative, more user-centred follow up study (Georgiou et al. 2015), we invited four stroke survivors (compared to one in the pilot study), three health professionals (a professor of nursing and two experienced physiotherapists) and three interaction designers. During this study, we engaged in in-depth discussions with all parties involved.

Two issues considered (Georgiou et al. 2015) were the way the devices are secured on the wearer's leg, and the control the of vibration intensity.

In the case of securing the devices, stroke survivors generally lose significant motor control on one of their hand as well as their leg (same side). That makes it difficult for them to secure a Velcro strap on their legs tightly enough. Difficulties in securing the devices on their legs without any assistance may put off users from using them, or as Mountain et al. point out: *'[…] any technological devices should be […] usable preferably without the help of the carer, to encourage independence […].'* (Mountain et al. 2006).

The current iteration of the HBIII system (currently under development) tries to tackle this design issue. In the new design, the Velcro straps are replaced by a tubular bandage holding all the electronic components. The user can then wear the HBIII devices as they would wear a pair of socks. The efficacy of this new strapping mechanism will have to be tested and evaluated with stroke survivors in another follow up study in the future (see Figure 3).

 Stroke survivors participating in our latest study (Georgiou et al. 2015) responded positively to the haptic cueing, however a significant point was made regarding the intensity of the vibration. Due to their condition, and depending on how severe their stroke episode was, stroke survivors may have different levels of sensitivity on their limbs. For example, what may be a clearly perceptible buzz to one survivor may not be at all detectable to another.

In the first HB iteration (HBI), the intensity could be adjusted via a physical wheel on the device and through the Wi-Fi network. However, during the redesign process, that wheel was removed and the only way for adjusting the vibration intensity was through the network. This added a significant burden to the network, which interfered with the overall quality of the haptic cueing (e.g. missed and

variable signal timings). In order to solve this, an Arduino Micro is used for controlling the total power received by the vibrotactiles via a technique known as Pulse Width Modulation (PWM). This allowed us to deliver haptic cues varying in intensity from a g-force of 0.5g all the way up to 10g, while retaining a well-shaped buzz via the dynamic braking of the vibrotactile motors.

In order to make the HB system more comfortable to wear, the 3D printed case protecting the electronic components for HBIII, has all edges smoothed and rounded to avoid catching on the wearers' clothes. Again, these new design features will be tested in future studies and interactive design workshops with stroke survivors and other major stakeholders (e.g. health professionals).
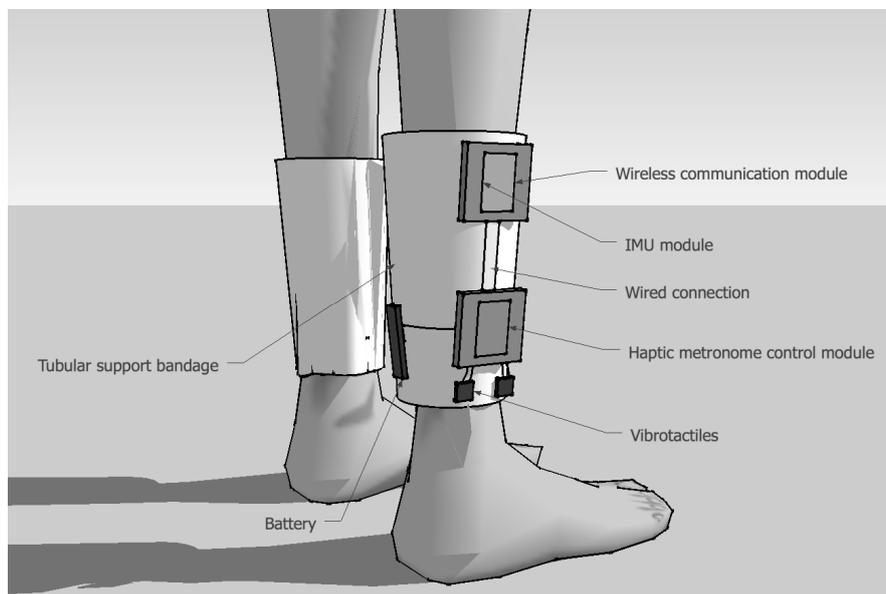
Fig. 3 Rendering of the latest Haptic Bracelet III prototype

5 Conclusion

Rhythmic cueing for entrainment is an important approach to gait rehabilitation for neurological conditions. In this paper we have outlined the theory behind this approach to rehabilitation. Walking to an audio or a visual rhythm has immediate, and sometimes lasting, gait related benefits. Haptic cueing has been shown in early pilot studies to be equally effective, and has the potential of being more suitable for use outside the controlled environment of the lab or clinic by end users. In particular, haptics leave sight and hearing unobstructed. This makes haptics particularly well suited for gait rehabilitation outside controlled environments such as labs and clinics. In this paper we have reported on three design iterations of the Haptic Bracelets, developed especially for this approach to gait rehabilitation. The designs have been guided by an on-going user-centred design evaluation process,

involving a wide range of stakeholders. Rhythmic haptic cueing for entrainment promises to open up new ways in which stroke survivors can take charge of their own rehabilitation.

References

Adamson J, Beswick A, Ebrahim S (2004) Is stroke the most common cause of disability? Journal of Stroke and Cerebrovascular Diseases 13(4): 171-177

Balasubramanian CK, Neptune RR, Kautz SA (2009) Variability in spatiotemporal step characteristics and its relationship to walking performance post-stroke. Gait and Posture 29(3): 408-414

Bank PJ, Roerdink M, Peper CE (2011) Comparing the efficacy of metronome beeps and stepping stones to adjust gait: steps to follow! Experimental Brain Research 209(2): 159-169

Benoit CE, Dalla Bella S, Farrugia N, Obrig, H, Mainka S, Kotz S (2014) Musically cued gait-training improves both perceptual and motor timing in Parkinson's disease. Frontiers in Human Neuroscience 8(494)

Bouwer A, Holland S, Dalgleish M (2013) The haptic bracelets: Learning multi-limb rhythm skills from haptic stimuli while reading. In: Holland S, Wilkie K, Mulholland P, Seago A (Eds.) Music and human-computer interaction, pp. 101-122. Springer, London, UK

Chen G, Patten C, Kothari DH, Zajac FE (2005) Gait differences between individuals with post-stroke hemiparesis and non-disabled controls at matched speeds. Gait and Posture 22(1): 51-56

Clayton M, Sager R, Will U (2005) In time with the music: The concept of entrainment and its significance for ethnomusicology. European Meetings in Ethnomusicology 11(1): 1-82

Galvin R, Cusack T, Stokes E (2009) To what extent are family members and friends involved in physiotherapy and the delivery of exercises to people with stroke? Disability and Rehabilitation 31(11): 898-905

Georgiou T, Holland S, van der Linden J, Tetley J, Stockley RC, Donaldson G et al. (2015) A blended user centred design study for wearable haptic gait rehabilitation following hemiparetic stroke. In: Proceedings of the 9th International Conference on Pervasive Computing Technologies for Healthcare, Istanbul, Turkey

Hillier S, Inglis-Jassiem G (2010) Rehabilitation for community-dwelling people with stroke: Home or centre based? International Journal of Stroke 5(3): 178-186

Holland S, Bouwer AJ, Dalgelish M, Hurtig TM (2010) Feeling the beat where it counts: Fostering multi-limb rhythm skills with the haptic drum kit. In: Proceedings of the 4th International Conference on Tangible, Embedded, and Embodied Interaction, Cambridge, MA, USA

Holland S, Wright RL, Wing A, Crevoisier T, Hödl O, Canelli M (2014) A gait rehabilitation pilot study using tactile cueing following hemiparetic stroke. In: Proceedings of the 8th International Conference on Pervasive Computing Technologies for Healthcare, Oldenburg, Germany

Intercollegiate Stroke Working Party (2012) National sentinel stroke clinical audit 2010 round 7. National and local results for the clinical audit 2010. Generic report prepared on behalf of the Intercollegiate Stroke Working Party and Royal College of Physicians

Kim CM, Eng JJ (2003) The relationship of lower-extremity muscle torque to locomotor performance in people with stroke. Physical Therapy 83(1): 49-57

Mountain GA, Ware PM, Hammerton J, Mawson SJ, Zheng H, Davies R et al. (2006) The SMART project: A user led approach to developing applications for domiciliary stroke

rehabilitation. In: Clarkson J, Langdon PM, Robinson P (Eds.) Designing accessible technology, pp. 135-144. Springer, London, UK

National Audit Office (2010) Progress in improving stroke care: Report on the findings from our modelling of stroke care provision. Audit Report, HMSO, London, UK

Nolan L, Wit A, Dudziñski K, Lees A, Lake M, Wychowañski M (2003) Adjustments in gait symmetry with walking speed in trans-femoral and trans-tibial amputees. Gait and Posture 17 (2): 142-151

Norvell DC, Czerniecki JM, Reiber GE, Maynard C, Pecoraro JA, Weiss NS (2005) The prevalence of knee pain and symptomatic knee osteoarthritis among veteran traumatic amputees and nonamputees. Archives of Physical Medicine and Rehabilitation 86(3): 487-151

Prassas S, Thaut M, McIntosh G, Rice R (1997) Effect of auditory rhythmic cueing on gait kinematic parameters of stroke patients. Gait and Posture 6(3): 218-223

Roerdink M, Lamoth J, Kwakkel G, Wieringen C, Beek J (2007) Gait coordination after stroke: Benefits of acoustically paced treadmill walking. Physical Therapy 87(8): 1009-1022

Schäfer C, Rosenblum MG, Kurths J, Abel H (1998) Heartbeat synchronized with ventilation. Nature 392: 239-240

Thaut MH, Kenyon GP, Schauer ML, McIntosh GC (1999) The connection between rhythmicity and brain function. Engineering in Medicine and Biology Magazine 18(2): 101-108

Thaut MH, Leins AK, Rice RR, Argstatter H, Kenyon GP, McIntosh GC et al. (2007) Rhythmic auditory stimulation improves gait more than NDT/Bobath training in near-ambulatory patients early poststroke: A single-blind, randomized trial. Neurorehabil Neural Repair 21(5): 455-459

Thaut MH, McIntosh GC, Hoemberg V (2015) Neurobiological foundations of neurologic music therapy: Rhythmic entrainment and the motor system. Frontiers in Psychology 5: 1-6

Thaut MH, McIntosh GC, Prassas SG, Rice RR (1993) Effect of rhythmic auditory cuing on temporal stride parameters and EMG. Patterns in hemiparetic gait of stroke patients. Journal of Neurorehabilitation and Neural Repair 7(1): 9-16

Vickhoff B, Malmgren H, Åström R, Nyberg G, Engvall M, Snygg J (2013) Music structure determines heart rate variability of singers. Frontiers in Psychology 4 (334)

Wright RL, Masood A, MacCormac ES, Pratt D, Sackley C, Wing A (2013) Metronome-cued stepping in place after hemiparetic stroke: Comparison of a one- and two-tone beat. ISRN Rehabilitation 2013(157410): 1-5