Rhythmic haptic cueing for gait rehabilitation of neurological conditions

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Restoring mobility and rehabilitation of gait are high priorities for rehabilitation of neurological conditions. Cueing using metronomic rhythmic sensory stimulation has been shown to improve gait, but most versions of this approach have used auditory and visual cues. In contrast, I propose the development of a prototype wearable system for rhythmic cueing based on haptics. The main aim of my research is to investigate how real-time gait monitoring and rhythmic haptic cueing can assist with gait rehabilitation for neurological conditions.

Entrainment; gait rehabilitation; stroke; walking; hemiparetic; haptic metronome

1. INTRODUCTION

Stroke is a sudden and devastating illness, affecting approximately seventeen million people worldwide each year (Stroke Association, 2016), with almost seven million people losing their life, making it the second single most common cause of death (World Health Organisation, 2014).

In the UK alone there are 1.2 million stroke survivors and over one hundred and fifty thousand new strokes occur every year (Stroke Association, 2016). Four out of five stroke victims survive their stroke (Stroke Association, 2016) (Townsend et al., 2012) but over half stroke survivors are left with a disability. This makes stroke one of the leading causes of complex adult disabilities (Adamson et al., 2004). Post-stroke disabilities have a higher impact on an individual than any other chronic disease (Adamson et al., 2004) (Royal College of Physicians Sentinel Stroke National Audit Programme (SSNAP), 2014) with more than half of all stroke survivors left dependent on others for every day activities (Stroke Association, 2016).

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).

Advances in technology mean that technology is increasingly finding its way into healthcare practices for either monitoring or as a medical intervention. Gait rehabilitation is one of the areas where technology is investigated as a means for assisting current practices.

Existing literature indicates that walking to a rhythm offers a number of gait-related benefits. Researchers exploring the idea of metronomic cueing using a variety of sensory channels, principally auditory, showed that immediate, though not lasting, walking benefits are possible. However, a number of impracticalities can be associated with these approaches making it difficult to move from the controlled environment of the lab to a self-managed home and outdoors setting.

For my research, I propose the investigation of a different sensory channel that may have the potential to overcome limitations of other approaches, making it possible for unsupervised rehabilitation exercises while achieving the same gait related benefits. This new proposed sensory channel is haptics; a term used for describing any form of non-verbal communication involving the sense of touch.
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More specifically, the aim of my research is to study how real-time gait monitoring and rhythmic haptic cueing can assist with the gait rehabilitation of people suffering from stroke and other neurological conditions.

My research question, as stated in the next section, stems from background knowledge in the literature that rhythmic cueing have beneficial outcomes when used to assist with gait rehabilitation. Preliminary results indicate that haptic cueing has the potential to be a practical solution for gait rehabilitation, with the potential of taking it outside the lab and using it in a more self-managed and unsupervised setting.

2. RESEARCH QUESTION

Gait rehabilitation after a person has suffered a stroke is of paramount importance for the restoration of independence and thus an overall better quality of life. This combined with evidence from existing literature that walking to a rhythm can benefit rehabilitation formed the primary motivation of my research leading to the following research question:

*How can real-time gait monitoring and rhythmic haptic cueing assist with the gait rehabilitation for neurological conditions?*

In order to clarify various background issues essential for the eventual refinement and expansion of this research question, a number of preliminary questions need to be addressed as part of the literature review and other early parts of this report.

(i) How can gait characteristics be monitored and quantified in the most efficient way for purposes of assisting with gait rehabilitation?

(ii) What are the factors that respectively assist or hinder people in using haptic cueing as part of their gait rehabilitation routine in an unsupervised, self-managed setting?

(iii) How can the efficacy of haptic cueing and monitoring be measured most suitably?

3. RESEARCH OBJECTIVES

Investigating the research question and providing clarifications to the issues identified, will help me move towards understanding and achieving the following aims:

Through iterative prototyping, I aim to develop a wireless wearable system capable of assisting with gait rehabilitation. More specifically, I aim to design and implement a system capable of monitoring certain gait characteristics of the person wearing it in real time and react by providing rhythmic haptic cueing when appropriate.

In addition, I aim to provide clinical evidence of the extent to which haptic cueing can benefit gait rehabilitation.

Lastly I aim to investigate which conditions need to be met for the system to be able to be used in unsupervised setting, such as at home and outdoors.

4. LITERATURE REVIEW

4.1 Stroke

Stroke is a life threatening condition that occurs when the blood supply to the brain is suddenly cut off. When brain cells are left without a blood supply, they begin to starve for oxygen and die. This loss of brain cells can lead to brain injury, disability and possibly death.

Stroke survivors commonly experience what is called hemiparesis. With hemiparesis, one side of the body is physically weakened, depending on the side of the brain that experienced the stroke incident. This condition subsequently affects the survivor’s gait, leading to what is called hemiparetic gait.

Hemiparetic gait is characterised variously by reduced walking speed (Olney, 1996), stride time variability (Balasubramanian et al., 2009), 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 & Eng, 2003) which can lead to joint pains (Norvell et al., 2005), degeneration (Nolan et al., 2003) and increased risk of fractures. Hemiparetic gait is directly linked to an increased risk of falling observed after stroke, doubling the risk of hip fracture (Pouwels et al., 2011). Besides the physical health issues, gait rehabilitation is also of paramount
importance for the restoration of independence and thus an overall better quality of life (Richards et al., 1993).

Carrying out rehabilitation exercises regularly can significantly improve a person’s recovery both in in the early days after a stroke and long after they return home (Galvin et al., 2009). Research in rehabilitation techniques strongly suggest that home-based rehabilitation is more beneficial to the patients (Hillier & Inglis-Jassiem, 2010; Fearon & Langhorne, 2012), but exercising in the home setting is not always easy as patients may have difficulty carrying out exercises effectively without suitable guidance.

Advances in technology mean that we are now in a position where it can be employed to assist individuals with day-to-day rehabilitation exercises. The field of research for improving gait rehabilitation is still open for further exploration, with strong evidence suggesting that metronomic cueing and entrainment (discussed further below) are effective in the rehabilitation and re-training after a stroke (Thaut et al., 2007) (Thaut et al., 1999) (Thaut et al., 2015).

4.2 Entrainment Basics

Entrainment is a natural phenomenon where two rhythmic processes interact with each other until they adjust to a common rhythm. This forms the underlying theoretical basis of my research, as it makes walking to a rhythm possible. The phenomenon was first identified in the field of physics and was later described in the domain of mathematics. It is only recently (early 1990s) that its biological application was identified and entrainment started to be studied as a way for movement rehabilitation of people suffering from neurological conditions.

4.2.1 Brief history

This phenomenon of entrainment was first identified by a Dutch physicist named Christiaan Huygens, in the late 17th century, as a result of his invention of the pendulum clock. When two such clocks, where placed on a common flexible support (i.e. a wooden mantelpiece), he noticed that the clocks’ 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 & Chong, 1999). He suspected that the two clocks were influencing each other through tiny vibrations in their common support. In order to test this he moved them to opposite sides of the room, and sure enough, the clocks fell out of step.

Huygens’ description of what he called ‘the sympathy of the clocks’, as well as the explanation he supplied, lead to the creation of a sub-branch of mathematics known as the theory of coupled oscillations, or entrainment (Strogatz & Stewart, 1993).

4.3 Entrainment and humans

The human body is full of naturally occurring rhythms, with the heart beating, respiration, and eyes blinking being just few of them. These endogenous rhythms may very easily entrain to each other within a single person, with an example being the synchronisation of respiration and heart rhythm patterns of choir singers (Vickhoff et al., 2013).

The concept of entrainment is adapted in gait rehabilitation where external rhythmic cueing are used for helping patients suffering from gait related disorders assume a symmetrical walking rhythm.

4.4 Rhythmic auditory stimulation

The human auditory system in general has evolved to be very good and efficient in detecting temporal patterns in auditory signals with extreme precision and speed. Thaut et al. in (Thaut et al., 1998) demonstrated that if a rhythmic auditory stimulus is provided, finger and arm movements can instantly entrain to the period of the rhythm. These movements can then stay locked to the rhythm even during subtle tempo changes.

This means that entrainment is not defined by the beat or the phase of the rhythm (Thaut et al., 2015). Having period entrainment is of utmost importance when considering controlling motor movement with RAS (i.e. in gait rehabilitation). Knowing the duration of the movement period the brain computes the next motor movement cycle, making the entire movement cycle fixed in time.

This gives the brain’s internal timekeeper mechanism an externally triggered mechanism with precise time intervals and a continuous time reference (Thaut et al.,
This means the brain knows how much time has elapsed since the movement started and more importantly how much time is left until the movement cycle must end, enabling enhanced anticipatory mapping and scaling of the movement ensuring optimal velocity and acceleration parameters during the movement cycle.

This process of an auditory rhythm providing a template the brain can follow to time movement, not only provides changes in the speed of the movement but it also makes it smoother and with less variable movement trajectories and muscle recruitment (Thaut et al., 2015).

Consequently, the motor timing is not the only aspect of movement that RAS is helping to control. The patterns of muscle activation are also affected providing comprehensive optimisation to the brain, making it possible to re-program movement (Thaut et al., 1999). This is another feature of entrainment that has clinical importance when talking about using RAS for motor rehabilitation.

By rewiring the brain timekeeping mechanism and changing the activation patterns of muscles patients can control the period of movement. Therefore, timing movement to an artificially introduced rhythm is possible and patients receiving rehabilitation do not need to synchronise their motor response exactly to the beat, as they would do in a stimulus-response model where the stimulus triggers the response. Stimulus response has indeed been found to be far less optimal in timing motor responses. In finger tapping experiments, for example, Thaut et al. (Thaut et al., 1998) demonstrated how the timing varies of the motor response to an audio beat in a stimulus-response model, whereas in entrainment conditions, human participants could keep to the period of the audio beat giving very precise responses even during frequency changes in the rhythmic interval.

4.5.1 Clinical results

Insights from studying the effects of RAS on motor movement, as discussed in the section above, led to the realisation that rhythmic cueing through the auditory channel has a great potential for assisting with the rehabilitation of rhythmic motion actions where coordination of muscles is necessary. With rhythmic entrainment, whole body movements, which are not usually driven by underlying biological rhythms, can be entrained.

The use of RAS in post-stroke gait rehabilitation indicates encouraging, though not lasting, positive results (Thaut et al., 2007). Studies involving participants walking on a treadmill showed that they could easily synchronise their steps to a rhythmic audio metronome (Roerdink et al., 2007). Having the walking rhythm dictated by the audio metronome also helped participants suffering from hemiparetic gait to show improvements in both spatial (e.g. stride length) (Prassas et al., 1997) and temporal (e.g. stride frequency) (Roerdink et al., 2007) symmetries while walking, in the step time asymmetry between the paretic and the non-paretic leg, and the variability of the paretic step time (Wright et al., 2013). In addition, participants in treadmill walking with RAS were able to make gait adjustments in response to phase shift of the audio rhythm (Pelton et al., 2010). These results indicate that RAS may have a strong clinical significance since step asymmetry is the leading cause of most of the problems associated with hemiparetic gait.

Entrainment through rhythmic stimulation is therefore, a very promising approach for assisting current gait rehabilitation techniques.

On the other hand, the use of audio may not be the best medium to convey the rhythm for entrainment if we want to consider moving the rehabilitation outside the controlled environment of a lab or a clinic and into the in-home and out-and-about scenarios. In these scenarios it is important to keep the audio channel clear in order to remain aware of the environment, oncoming traffic or even when trying to hold a conversation with other people.

Maintaining a free from distraction auditory channel may not be a problem if rehabilitation is kept within a supervised environment in the lab or clinic. However, evidence suggests that rehabilitation in the home environment can be more beneficial (Hillier & Inglis-Jassiem, 2010). The approach of self-managed rehabilitation also 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).

Therefore, there is a clear need for something practical and non-intrusive that can provide a rhythmic cue for gait rehabilitation. There is a clear gap and a need for a method of giving the rhythm to the person receiving gait rehabilitation in a way that is not intrusive as it is in the case of audio and visual cues and does not require extensive installations to operate. A possible solution may be through the use of haptics (i.e. sense of touch).

4.6 Haptic cueing

Haptics is a term used when referring to anything that has to do with the sense of touch, and can provide another mode for transferring rhythmic cueing for entrainment and motor movement rehabilitation. Even though rhythmic haptic cueing has shown promising results and great potential of offering similar and immediate benefits similar to auditory cue (Holland et al., 2014), there is not much literature exploring how it can be used for motor movement rehabilitation. The literature concerning haptic cueing mostly focuses on stimulus response mechanism for conveying messages and notifications (e.g. (Brewster & Brown, 2004)) or for helping in improving limb awareness in chronic stroke (Luster et al., 2013). One possible reason for this apparent underuse of rhythmic haptic cueing may be the evident tension that exists between the notion of stimulus-response and the notion of entrainment (Georgiou et al., 2015). It is often not clearly understood that due to physiological delays, stimulus response is not a viable way to consciously synchronise to rhythm (Bouwer et al., 2013). Entrainment, on the other hand (as discussed earlier), can provide the fine-grained synchronisation that allows one’s movement to synchronise to an external rhythm both physically and mentally.

5. INITIAL RESULTS

In an earlier pilot study where rhythmic haptic cueing was used (i.e. as vibrations on the skin) (Holland et al., 2014), the participant’s step length was found to increase, while a range of other measures such as the paretic, 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.

Contrary to the other approaches, the spatial arrangement of delivering haptic cues can be customised, with different spatial placement used to manipulate attention and proprioception in particular cases for enhanced therapeutic benefit. This is something that, to the best of my knowledge, needs further investigation.

In a follow-up pilot that focussed more on qualitative data (Georgiou et al., 2015), participants were asked to walk using a rhythmic haptic cue for reference and asked to comment on their experience. Their comments were positive and they all seemed to like the haptic cue. One participant told us afterwards: "The beat (rhythm) is, it’s something to listen to. [...] the rhythm is good for me."

Since then, I continued with the iterative design approach (see below), producing and testing prototypes of wearable devices to monitor gait and deliver a rhythmic haptic cueing, based on user’s feedback and lab evaluation results.

6. RESEARCH APPROACH

Given that the aim of my research is to investigate how rhythmic haptic feedback can be used to assist with the gait rehabilitation of people suffering from neurological conditions, my research approach falls primarily into four parts.

The first part is one that relies on quantitative data and can be further divided in two parts: data to validate the correct working of the prototype devices, and data to indicate the level of efficacy of the devices. For both parts statistical analysis will be used to quantify and compare the data, but for the second part, expert interpretation of the analysis will be necessary for giving clear evidence for improvements in gait.

The second part focuses primarily on qualitative data. Relying purely on quantitative data is not sufficient when designing a system intended for people to use and potentially incorporate into their day-to-day life. Therefore, actual users must be involved throughout the designing, testing and implementation phases. Users must come from all aspects of the rehabilitation process: patients and health professionals. An early study carried out prior to this study (Georgiou et
al., 2015), employed user-centred design methods such as interviews, participatory design and usability testing. This kind of qualitative research methods can provide a vast array of important insights regarding the haptic cueing and the prototype design and evaluation.

The third part concerns the prototyping nature of this research. Even though there is existing literature indicating that rhythmic cueing and entrainment, the underlying theory of this research is proved to work, my approach of using haptics to deliver is novel, without much literature to rely on. Therefore, I will need to continuously re-design and re-evaluate my prototypes throughout the duration of this research. This process is known as iterative design; a design methodology based on a cyclic process of prototyping, testing, analysing, and refining a prototype based on the results of testing the most recent iteration of a design, with changes and refinements being made. Finally, the fourth part of my research approach concerns the evaluation of my system’s design and performance in the wild (i.e. outside the controlled environment of the lab.) Such in the wild studies involve observing how users interact with the system while keeping an eye out for any issues or conditions that may influence user interaction. It is too early to know the exact shape these “in the wild studies” will take but they will very likely involve ethnographic methods of obtaining information from users (through observations and interviewing) and may also include quantitative data from the devices sensors regarding their use.

It is very important to stress out at this point the importance of in the wild studies when designing technology for humans. Wearable devices and new pervasive healthcare systems need to show how they can fit in with someone’s lifestyle by being comfortable and easy to use and their benefits must be clear to the wearer. To assess this technology requires evaluating them in the wild since findings from lab experiments do not always carry over (van der Linden et al., 2011) with different patterns of usage frequently being observed between the two. This highlights how a variety of context factors, with the physical environment being one of them, needs to be taken into account when deploying a new technology in situ.

For example, (Rogers et al., 2007), (Spelmezan et al., 2009) and (Jambon & Meillon, 2009) demonstrate how technology was not used in the way they initially envisioned when taken to a real life setting (in the wild). In addition, a study curried out by (Hoggan & Brewster, 2010) further highlight the importance of in situ studies by demonstrating how certain modalities work better in some environments than others.

Therefore, broadly speaking, the research approach in this study needs to cover a number of different areas, each having a different research approach. The parts discussed in the paragraphs above will run simultaneously for most of the research’s length with mixed methods being used throughout research and development of the system. Each part will have a significant amount of input and influence on both the methods and the approach used in every step taken.

7. MAIN CONTRIBUTIONS

The main contributions will be primarily a considerable body of empirical evidence pointing towards the efficacy of using rhythmic haptic cueing for gait rehabilitation. This empirical evidence will be both quantitative and qualitative, taking special interest in the human aspects.

Another contribution will be a high fidelity gait monitoring system, capable of monitoring a person’s movements at a fine grain, analyse them and provide haptic rhythm whenever needed. This system will come through the iterative design methodology, taking the results of each study as an inspiration for the next step. This system will ultimately be capable to operate autonomously in a self-managed environment allowing enhanced gait rehabilitation to extend outside the clinic and into the patients’ homes.
8. REFERENCES


Norvell, D.C. et al., 2005. The prevalence of knee pain and symptomatic knee osteoarthritis among veteran traumatic


