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Wearable Haptic Devices for Gait Re-education by Rhythmic Haptic Cueing

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This research explores the development and evaluation of wearable haptic devices for gait sensing and rhythmic haptic cueing in the context of gait re-education for people with neurological and neurodegenerative conditions. Many people with long-term neurological and neurodegenerative conditions such as Stroke, Brain Injury, Multiple Sclerosis or Parkinson's disease suffer from impaired walking gait pattern. Gait improvement can lead to better fluidity in walking, improved health outcomes, greater independence, and enhanced quality of life. Existing lab-based studies with wearable devices have shown that rhythmic haptic cueing can cause immediate improvements to gait features such as temporal symmetry, stride length, and walking speed. However, current wearable systems are unsuitable for self-managed use for in-the-wild applications with people having such conditions. This work aims to investigate the research question of how wearable haptic devices can help in long-term gait re-education using rhythmic haptic cueing. A longitudinal pilot study has been conducted with a brain trauma survivor, providing rhythmic haptic cueing using a wearable haptic device as a therapeutic intervention for a two-week period. Preliminary results comparing pre and post-intervention gait measurements have shown improvements in walking speed, temporal asymmetry, and stride length. The pilot study has raised an array of issues that require further study. This work aims to develop and evaluate prototype systems through an iterative design process to make possible the self-managed use of such devices in-the-wild. These systems will directly provide therapeutic intervention for gait re-education, offer enhanced information for therapists, remotely monitor dosage adherence and inform treatment and prognoses over the long-term. This research will evaluate the use of technology from the perspective of multiple stakeholders, including clinicians, carers and patients. This work has the potential to impact clinical practice nationwide and worldwide in neuro-physiotherapy.

Wearables, Haptics, Long-term, Gait, Rhythm, Neurological, Neuro-physiotherapy

1. INTRODUCTION

Many people with conditions such as Stroke, Brain Injury, Multiple Sclerosis and Parkinson's disease develop gait abnormalities. Such gait impairments can lead to increased metabolic cost of walking, increased risk of falls, fracture, joint degeneration, and loss of bone mineral density (Hollands et al., 2012). In such cases, walking can be improved by non-invasive therapeutic interventions for gait re-education (Tate and Milner, 2010). Typically gait re-education takes place within clinical settings under the supervision of physiotherapists. Over the long-term, access to physiotherapy is expensive and tends to be rationed. Wearable sensing and feedback devices have been considered for self-managed, long-term physiotherapy outside the clinical setting (Chen et al., 2017).

Shull et al. have (2014) surveyed wearable feedback methodologies for abnormal gait

intervention and have identified three sensory channels presently used for such therapeutics: auditory, visual and haptic. Previous studies using rhythmic audio and visual cueing have shown improvements in gait for people with different neurological conditions (Thaut and Abiru, 2010). Gait re-education through haptic modality has shown promising results in the lab (Georgiou, 2018; Holland et al., 2014) providing safe, unobtrusive and discrete alternative to other modalities (Thaut and Abiru, 2010).

Wearable haptic devices providing rhythmic haptic cueing to people with neurological conditions for gait re-education is a promising avenue for research. This work aims to investigate the potential of using self-managed wearable haptic devices in-the-wild for long-term gait re-education via rhythmic haptic cueing as the therapeutic intervention.

2. RESEARCH QUESTIONS

This work aims to investigate the primary research question:

How can wearable haptic devices help in long-term gait re-education using rhythmic haptic cueing?

In order to address the primary research question, a number of secondary questions need to be addressed as well:

- (i) How can efficacy of rhythmic haptic cueing as a therapeutic intervention for long-term gait re-education be measured?
- (ii) How can real-time, remote gait monitoring assist clinicians track dosage adherence and prognosis?
- (iii) How can interaction design issues (wearability, usability, unobtrusiveness) be addressed within the constraints of the technical issues (portability, network latency, power efficiency) and clinical requirements (gait monitoring, dosage adherence, prognosis)?

3. RESEARCH OBJECTIVES

In relation to the research questions mentioned above, the primary objective of this work is to investigate: how wearable haptic devices can help in long-term gait re-education using rhythmic haptic cueing as a therapeutic intervention.

To meet that objective, a system would be developed that can provide rhythmic haptic cue as a therapeutic intervention. Additionally, the system would also be able to monitor gait remotely to track dosage adherence and prognosis. Thus, attempting to measure efficacy of the therapeutic intervention over the long-term.

The system would be developed through an iterative design process addressing self-managed use, and identifying key interaction design, usability and technical requirements. Also, this work would evaluate the use of technology for therapeutic intervention and remote monitoring to inform clinicians, carers and patients.

4. LITERATURE REVIEW

This section discusses the existing literature in relation to the proposed research question and identifies potential gaps within existing work.

4.1 Rhythmic Cueing for Gait Re-education

Studies have shown that external rhythmic cueing can be promising for walking rehabilitation

(Hollands et al., 2012). Chronic stroke survivors were able to synchronize to an auditory metronome while walking on a treadmill (Roerdink et al., 2007). Auditory pacing has shown improvements in step time variability (Wright et al., 2013), spatial (Prassas et al., 1997) and temporal symmetry (Roerdink et al., 2007). In comparison to typical gait rehabilitation (Thaut et al., 1997) and Bobath training (Thaut et al., 2007), auditory cueing has shown significantly better improvements in walking speed and stride length. Other studies have shown that visual or auditory cueing can improve gait for Parkinson's disease patients (Suteerawattananon et al., 2004) and can also address freezing of gait (Donovan et al., 2011).

It is suggested that the brain calculates the time period of the external rhythm and in turn sets the time period for the oscillation of the limbs (Grahn & Brett, 2007). This attempt of the brain to emulate the period of the rhythm helps motor coordination to become synchronized to an exact harmonic period therefore improving walking gait pattern.

Another interpretation of the phenomenon is that the external rhythm acts as a template for the brain to emulate for motor coordination by interacting with the neural Central Pattern Generator (Thaut et al., 1992). This allows the motor movement to become more oscillatory, with induced muscle activation, improvement in speed and less variability in motion trajectory (Thaut et al., 2015).

The reprogramming of motor coordination and muscle reactivation is a product of neural plasticity which is triggered by rhythmic cueing (Thaut et al., 1999). Numerous physiotherapy approaches rely upon the principle of neural plasticity for improved motor coordination by repeated exposure to normalised movement patterns (Patterson et al., 2008). Rhythmic cueing is a viable intervention for gait re-education that can induce neural plasticity through repeated exposure to an optimised movement pattern (Hollands et al., 2012).

4.2 Use of haptic modality for rhythmic cueing

Haptic cueing is an unobtrusive method to provide external rhythm to induce neural plasticity for gait re-education. By using haptic cueing, it is possible to cater for personal preferences in terms of location and specificity. For example, depending on preference, haptic cueing could be provided to legs, ankles, feet or arms. Also, if sensation between any of the body parts is varied it could be useful to specify a particular side of the body, preferring the right leg over the left leg for example (Belda-Lois et al., 2011). This could be potentially beneficial for proprioception in sensorimotor rehabilitation.

In regular practice, therapists use touch to help patients to stabilize, to reduce postural sway and to

improve gait symmetry. Haptic cueing can help increase stride length while promoting regular gait and posture (Sejdić et al., 2012). Haptic cueing is potentially a better alternative to other forms of external cueing for daily usage. With a mobile, lightweight, robust, wearable, and pervasive haptic device, gait re-education could be taken out of therapy clinics and labs to the home, and feasibly outside in-the-wild. Small-scale studies have been conducted using haptic devices for gait re-education with promising results (Georgiou et al., 2015; Holland et al., 2014), however, further research is required to investigate the potential of rhythmic haptic cueing for long-term gait re-education.

4.3 Wearable haptic devices for rehabilitation

Haptics devices can be used to utilize the sensation of touch to provide external rhythmic cueing for gait rehabilitation. Wearable devices providing haptic cueing for such rehabilitation potentially offers similar benefits in the wild to the proven benefits of an audio cue in the lab. Use of vibrotactile feedback has shown improvements in temporal gait symmetry for elderly patients with lower limb amputations (Crea et al., 2017). Wang et al. (2017) performed a rigorous systematic review of wearable devices for upper body rehabilitation, where they compared the different modalities for external cueing including haptics. A pilot study was conducted involving a wearable device on the paretic arm for a stroke survivor as means of cueing the patient to use their arm outside their regular therapy sessions, to prevent disability due to lack of use (Luster et al., 2013). Zishi, a wearable upper body exoskeleton, was developed to provide real-time haptic feedback to monitor and correct posture for survivors of stroke, multiple sclerosis and Parkinson's disease (Wang et al., 2016).

Although CueS (Holden et al., 2015), a wrist-worn haptic cueing device, was primarily designed for people with upper limb dexterity issues, both participants with stroke and Parkinson's disease took part in the study. Parkinson's disease patients attended a participatory design workshop, while stroke patients participated in an in-the-wild pilot evaluation study. The evaluation study was 2 weeks long where the 1st week consisted of data logging and benchmarking phase, with the 2nd week being the cueing phase. Some older studies have used haptic or electrotactile stimulation on sensate regions such as the skin of unaffected limb or torso to improve grasp for people with spinal cord injury (de Castro & Cliquet, 2000) and Multiple Sclerosis (Jiang et al., 2009). In a separate proof of concept study, delivering subsensory vibratory noise via stochastic resonance from a shoe insole showed improvements in gait and balance for healthy elderly adults (Lipsitz et al., 2015), even

though this study did not include subjects with neurological conditions, a similar previous study was performed on people with stroke (Priplata et al., 2006).

These studies confirm the use of haptics in rehabilitation and gait re-education and also explore the aspect of expanding therapeutic interventions outside of clinical and lab settings. All of the above studies make use of the stimulus-response mechanism of the body for feedback and rehabilitation. Crucially, except for (Georgiou et al., 2015; Holland et al., 2014), the other studies did not take into consideration the phenomenon of rhythmic cueing. The CueS study (Holden et al., 2015) attempted a 2-week long study phase, however, long-term benefits of such rehabilitation techniques are yet to be explored in a systematic manner. Using wearable haptic devices, it is also possible to exert cueing on specific parts of the body, altering the rhythm if required, providing the ability to manipulate attention and proprioception for therapeutic benefit.

4.4 Usability of wearable devices for rehabilitation

Usability issues are among the key hindrances to adoption of rehabilitation technologies for patients (Steele et al., 2009). Mazilu et al (2014) pointed out four main issues on why such wearable technologies have low adoption rates. Although their suggestions are mainly based on Parkinson's disease patients, similar traits are seen in other neurological conditions as well (Georgiou, 2018). The four main issues are:

- (i) **Obtrusiveness:**
The weight, bulkiness, number and location of devices attached to the body decides the comfort level of the systems for a user's perspective. Especially, people with motor impairments can face difficulties wearing the devices. The devices may be mounted with Velcro straps, belts, integrated into cloths or glued to the skin. Overall, the devices function more reliably if they are secured tightly to the body. Although attaching multiple devices or sensors may lead to more accurate and reliable system, however, that would increase obtrusiveness and difficulty in self-management.
- (ii) **Stigmatization:**
Wearable technologies that are visible to other people may lead to a feeling of stigmatisation. Especially, if the systems are worn permanently for regular monitoring and support.
- (iii) **Feedback:**
Users anticipate regular feedback from the

systems as means of reassuring them of the system functionality and thus increases trust in the system.

- (iv) Other issues that usually come up while designing wearable technologies for such user base are related to privacy, security, reliability and battery life. Although some of these issues are technical rather than usability, however, these are trade-offs that would need to be addressed during the design process.

Similarly, research has shown that engaging users during the design process improves acceptability, trust towards the system and overall usability (Uzor & Baillie, 2013). Keeping the above factors into consideration, the design and technical trade-offs can be explored in a user-centred design process.

4.5 Outcome Measures

In regular physiotherapy practice, there are certain best practices for quantitative and qualitative outcome measures for gait assessment for people with neurological conditions, drawing particularly on Moore et al., (2018). The Berg Balance Scale, Activities-Specific Balance Confidence Scale and Functional Gait Assessment are used to assess changes in balance and stability. The 10 Metre Walk Test is used to assess changes in gait speed and the 6 Minute Walk Test is used to assess changes in walking speed. Although not part of best practices, there are a number of outcome measures that can be used to assess patient-specific goals. In addition to the above outcome measures there are other quantitative measures such as walking speed, cadence, stride length, spatio-temporal gait symmetry and variability that can be used to assess changes in gait measurements in clinical or lab settings for pre and post intervention (Casamassima et al., 2014). Hollands et al. (2012) have reviewed numerous studies related to gait rehabilitation for stroke survivors. They have shown that the validity of gait symmetry as a goal for rehabilitation post-stroke is controversial as it not a proper measure of motor coordination. Even though some studies have shown that temporal gait asymmetry to a certain extent is correlated with motor recovery, walking speed, strength, spasticity, and falls. People suffering from gait asymmetry have a higher metabolic cost of walking, increased risk of joint degeneration and loss of bone density in the weaker limb.

Outcome measures during the intervention phase over the longer-term is insufficient to inform clinicians to adapt therapies and medications for individual needs (Steins et al., 2014). This work would attempt to investigate potential outcome measures for such scenarios to measure dosage

adherence and prognosis using wearable devices to better inform the clinicians.

4.6 Towards Long-Term Gait Re-education

This section explores the research potential in long-term gait re-education via rhythmic haptic cueing. Harrison et al., (2018) conducted a review on effectiveness of external cueing on people with neurological conditions. They have compared different modalities of cueing but identified only one study that have used haptic cueing for gait re-education (El-Tamawy, Darwish, & Khallaf, 2012). This double blind longitudinal randomised controlled trial examined proprioceptive neuromuscular facilitation and vibratory stimuli with 30 Parkinson's disease patients and compared with a control group provided with no cues for about 8 weeks. Walking speed and mean cadence were observed to be better in the intervention group.

However, Harrison et al., (2018) on comparing the available evidences, could not conclude the most appropriate modality for such cueing for gait improvements as it was difficult to judge between the variety in cueing methods, outcomes measures and the wide variety in individual differences between subjects and variations between different neurological conditions. They have also mentioned that majority of the studies provided short-term cueing with a small number of studies lasting for about 1-2 months. Studies suggest that in order to see a sustained beneficial effect the therapeutic intervention should span for a longer time and may even last for at least six months (Ashoori et al., 2015). However, none of the reviewed studies span for such appropriate length of cueing therapy.

Harrison et al., (2018) further mentions that future studies should therefore examine the long-term benefits of cueing and if the improvements could be sustained in people with neurological conditions over time.

Such research would determine the length of therapy sessions with external cueing required to see a sustained beneficial effect. This would not only have potential positive effects towards activities such as walking for but may also improve their quality of life and reduce the burden on carers (Foster et al., 2014).

A recent longitudinal pilot with rhythmic haptic cueing for over 2 weeks have shown promising results in gait re-education for a brain trauma survivor (Islam et al., 2018). Improvements in walking speed, gait symmetry and cadence were observed along with implications on positive impact on confidence, quality of life and encouraging more physical activity. These promising results and research directions mandates further research in this area. The following section summarises the

key findings from the literature review and identifies potential gaps.

4.7 Key Points of Literature Review

In summary, the existing literature has been analysed from a number of different angles such as presenting the potential of rhythmic haptic cueing for gait re-education, exploring the use of technology such as wearable devices in providing rhythmic haptic cueing and also sensing gait parameters, understanding the technical and usability aspects of such technological solutions, discussing the outcome measures to measure efficacy of rhythmic haptic cueing as a therapeutic intervention and finally exploring the long-term prospects of such intervention in gait re-education for people with different neurological conditions. On doing so a number of interesting themes have emerged:

- Numerous studies have shown that rhythmic auditory cueing can bring about improvements in gait pattern for different neurological conditions, and similarly studies have been conducted to assess sustained long-term benefits, even though such understanding is not particularly clear.
- Rhythmic haptic cueing presents a promising alternative modality to auditory cueing with potentially similar benefits. Small scale studies have been conducted with promising results, however, exploring such sustained benefits over the long-term has been limited.
- From a technological and usability perspective, a number of design trade-offs have to be considered.
- There are standard outcome measures for assessing changes in gait for pre and post intervention, however, outcome measures suitable for personalized long-term care to show dosage adherence and monitor prognosis is not clearly understood yet.

These emerging themes can be considered as potential gaps within the literature, that would require further investigation. Thus, taking these under consideration the following section would further discuss the proposed research questions.

5. RESEARCH METHODOLOGY

This section outlines the underlying methodology to investigate the proposed research questions. The primary methodology for this work would be a 'technology probe' (Hutchinson et al. 2003). Prototype wearable haptic devices would be considered as the technology probe for this work.

The use of a technology probe nicely fits the exploratory nature of this work.

Hutchinson et al (2003) explains the technology probe as, "Technology probes are a particular type of probe that combine the 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 and desires. A well-designed technology probe should balance these different disciplinary influences." This interpretation of the technology probe methodology would be the main principle for this work by binding the clinical requirements and the design or usability issues to the technology probe.

Figure 1 visualises the use of the technology probe to investigate the proposed research questions.

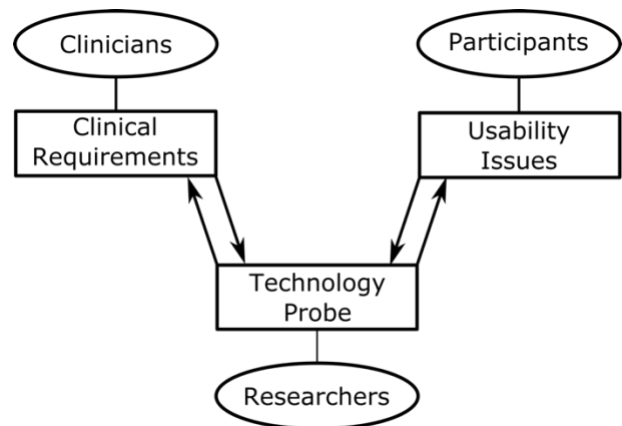


Figure 1: Researchers using Technology Probe to relate Clinical Requirements from Clinicians and Usability Issues from Participants

The left-hand side of the figure would address research questions:

- (i) How can efficacy of rhythmic haptic cueing as a therapeutic intervention for long-term gait re-education be measured?

and,

- (ii) How can real-time, remote gait monitoring assist clinicians track dosage adherence and prognosis?

related to the clinical requirements of this work. Whereas, the right-hand side of the figure would address research question:

- (iii) How can interaction design issues (wearability, usability, unobtrusiveness) be addressed within the constraints of the technical issues (portability, network latency, power efficiency) and clinical requirements (gait monitoring, dosage adherence, prognosis)?

related to the interaction design or usability issues of the participants.

As previously mentioned, "...collecting information about the use and the users of the technology in a real-world setting, the engineering goal of field-testing the technology...", the technology probe would facilitate testing the technology in-the-wild and would assist identification of key interaction design, usability and technical issues. Huang et al (2014) adapted the technology probe methodology for an iterative design of a home-based knee rehabilitation system by binding the user requirements with physiotherapists' requirements. Huang (2015) also stated that, "A technology probe will be of little value if the system's main function is defective. In this regard, [the probe] needed to capture patient exercise movements accurately. Therefore, it was necessary to validate this functionality of [the probe]."

For this work, a similar approach would be taken to address the proposed research questions by combining the user's needs with clinical requirements.

6. STUDY DESIGN

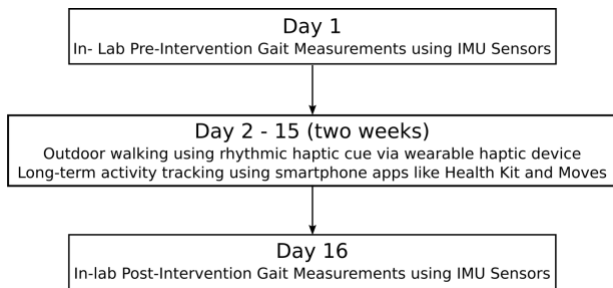


Figure 2: Study Design for Pilot Study

The design (Figure 2) for an initial pilot study, (using an off-the-shelf wearable haptic device which provided a rhythmic haptic pulse) involved a two-week period of walking outdoors while trying to synchronise footfalls to the rhythm. Long-term activity tracking was carried out using an iPhone running the Health Kit and Moves apps. Inertial Measurement Unit (IMU) sensors were used to measure gait before and after intervention. The sessions were video recorded for physiotherapists to evaluate the pre and post-intervention gait.

7. PRELIMINARY RESULTS

Walking speed, cadence, step length and temporal asymmetry were calculated and compared against pre and post-intervention results from data obtained from IMU sensors and video recordings.

The comparison between mean gait measurements pre and post-intervention is presented in Table .

Percentage change and T-test were calculated as appropriate. The results showed statistical significance for improvements in walking speed, cadence and step length respectively. Temporal asymmetry decreased, implying improved symmetry of walking.

Table 1: Comparison of Gait measurements pre and post-intervention

Measurements	Pre	Post	% Change	P – value
Walking Speed (m/s)	0.84	0.93	+10.71	< 0.001
Cadence (steps/min)	87	92	+5.95	< 0.01
Step Length (m)	0.58	0.60	+3.45	< 0.01
Temporal Asymmetry	2.20	2.08	-5.45	_____

Two neurophysiotherapists evaluated the walking pattern of the participant and confirmed the improvements identified by preliminary quantitative results.

Their evaluation can be summarised as follows:

- (i) several improvements observed,
- (ii) some existing impairments unchanged,
- (iii) no new impairments observed.

Changes in gait following intervention:

- (iv) improved gait symmetry,
- (v) improved stability and balance.

These preliminary results overall showed improvements in the participant's gait pattern, with potential implications for confidence, independence and quality of life.

8. MAIN CONTRIBUTIONS

The main contributions of this work would be:

- A body of knowledge on the efficacy of rhythmic haptic cueing for long-term gait re-education.
- A framework addressing key interaction design, usability and technical issues of wearable systems for gait re-education. This framework can be used as a tool for system design for similar use cases in the future.
- Data sets and insights into real-time, gait monitoring for dosage adherence and prognosis. These can help clinicians better plan their therapies and medications catered to their patients' needs.

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