Questioning classic patient classification techniques in gait rehabilitation: insights from wearable haptic technology

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Abstract. Classifying stroke survivors based on their walking abilities is an important part of the gait rehabilitation process. It can act as powerful indicator of function and prognosis in both the early days after a stroke and long after a survivor receives rehabilitation. This classification often relies solely on walking speed; a quick and easy measure, with only a stopwatch needed. However, walking speed may not be the most accurate way of judging individual's walking ability. Advances in technology mean we are now in a position where ubiquitous and wearable technologies can be used to elicit much richer measures to characterise gait. In this paper we present a case study from one of our studies, where within a homogenous group of stroke survivors (based on walking speed classification) important differences in individual results and the way they responded to rhythmic haptic cueing were identified during the piloting of a novel gait rehabilitation technique.

Keywords: Stroke, classification, rhythmic haptic cueing, Haptic Bracelets.

1 Introduction

Stroke is a sudden and devastating illness, affecting approximately seventeen million people worldwide each year [1], making it the second single most common cause of death. Four out of five stroke victims survive their stroke [1] but over half stroke survivors are left with a disability, making stroke one of the leading causes of complex adult disabilities [2]. Post-stroke disabilities have a higher impact on an individual than any other chronic disease [2] with more than half of all stroke survivors left dependent on others for everyday activities.

Current research has shown that walking to a rhythm can lead to significant improvements in various aspects of gait for stroke survivors, such as temporal and spatial asymmetries [3] [4] [5] [6]. The benefits of walking to a rhythm, as a form of therapy for such conditions, are well established. However, most studies fail to identify individual differences between participants and tend to treat them as a homogenous group.

The primary aim of our study was to explore the concept of rhythmic haptic (touch based) cueing as an alternative to the more established audio rhythm used for gait rehabilitation. This study enabled us to gather the views of stroke survivors and health professionals through hands-on involvement with a new technology. In particular, we were exploring the possibility of using a small wearable prototype device we designed, called *The Haptic Bracelets*, to deliver haptic cueing in an appropriate rhythm for walking. The Haptic Bracelets are lightweight devices wearable on both limbs at ankle level, that are capable of monitoring and analysing gait and delivering rhythmic haptic cueing via low latency vibrators on alternating legs [7].

During our study, motion capture data was collected and analysed to help identify design questions, characterise issues relevant to the future design and operation of the technology and to refine our understanding of the context of use and the theoretical background. A previous paper [8] considered data from questionnaires, interviews, and from dialogues between stroke survivors, health professionals and interaction designers that were carried out during sessions. In this paper we consider the issues and questions raised in the context of the analysis of the motion capture data.

Using traditional grouping measurements, based on gait velocity measured with a stopwatch, all our participants were classified as having the same ambulatory capability. However, the kinematic data we collected showed some major individual differences and we argue that such differences can play an important role during rhythm based gait rehabilitation interventions.

New technologies like the Haptic Bracelets can help establish other measures that might play a useful role in physiotherapy practice. Amongst other applications for diagnosis, monitoring and therapy, the Haptic Bracelets can provide richer data for a more accurate classification of stroke survivors based on their walking capabilities. It is this particular application that we explore in this paper.

2 Background

2.1 Post stroke gait impairments

Gait coordination is often compromised after stroke with survivors experiencing what is known as “hemiparetic gait”; a condition commonly characterised by reduced walking speed [9], stride time variability [10], increased step length variability [10], and temporal and spatial gait asymmetry [11].

Many health problems are associated with this condition. The non-paretic (stronger) limb may be exposed to higher vertical forces [12] which can in turn lead to joint pains due to increased repetitive loading [13], bone degeneration [14], and increased risk of fractures. Hemiparetic gait is also directly linked to an increased risk of falling observed after stroke, doubling the risk of hip fracture [15]. Besides physical health issues, gait rehabilitation is also of paramount importance for the restoration of independence and thus an overall better quality of life [16].

Chronic stroke survivors (6+ months after their stroke incident) generally exhibit hemiparetic gait, which limits function and can restrict participation in society. However, due to neuroplasticity, even at this later stage motor relearning is still a possibility [17]. Gait recovery is one of the major goals in post-stroke rehabilitation [18]. Therefore, for many decades, hemiparetic gait has been the object of study for the development of methods for gait analysis and rehabilitation [19].

2.2 Rhythmic cueing for gait rehabilitation

Use of an auditory rhythm provided by a metronome has been investigated and successfully demonstrated as a means of improving hemiparetic gait with immediate, though not necessarily lasting, effects [3] – although studies for other neurological conditions that affect gait suggest that with extended training, effects can last for weeks [20].

Studies where participants were asked to walk on a treadmill showed that they could synchronise their steps to a rhythmic audio metronome [21]. Audio cues also helped participants with post-stroke gait impairments to show improvements in spatial [22] and temporal symmetry [21]. The step time asymmetry and the paretic (affected leg) step time variability of participants also improved significantly [23], as did the ability to make gait adjustments in response to changes in the cue [24]. Rhythmic cueing is therefore a promising approach, but the use of audio may not be the best medium for in-home or out-and-about scenarios for rehabilitation, where it is important to keep the audio channel clear for reasons of safety, sociability, and to remain aware of the environment. With audio cues alone it is difficult to differentiate which cue is for which leg [23], thus missing out on some potentially beneficial aspects of attention and proprioception in gait rehabilitation.

2.3 The role of entrainment

Rhythmic cueing is based on entrainment models. In physics, entrainment is a natural phenomenon where two or more periodic processes interact with each other to adjust to a common or related period. However, it was only recently (early 1990s) that the human capacity for biological entrainment became better understood and applications for movement rehabilitation of neurological conditions were studied. As discussed above, applications included the use of auditory cues to synchronise human motor responses into stable time relationships. In such cases, biological entrainment mechanisms act between the external rhythm and the motor response to stabilise and regulate gait patterns [3].

When considering cues for movement, it is important to distinguish between stimulus response models and the biological entrainment model. With the stimulus-response model, as the name suggests, the user responds directly to each stimulus. By contrast, after hearing a few initial beats, most people can generally tap along to a regular pulse in more or less exact synchronisation. Consequently, entrainment is the common foundation for the various applications of metronomic rhythmic sensory stimulation in any modality.

2.4 Patient/participant ambulatory classification

Classifying stroke survivors based on ‘ambulation capability’ is an important aspect of rehabilitation treatment. Historically, gait velocity is shown to have predictive validity for rehabilitative outcome. After reviewing gait related classification techniques, ranging from stroke survivors’ self-assessment questionnaires to motor control tests performed by health professionals, Perry et al. [25] concluded that when treated as an independent measure, gait velocity has strong potential for classifying people based on what is referred to as their ‘community walking status’. Less than 0.4 m/s predicts household walking; 0.4 to 0.8m/s predicts limited community walking; and more than 0.8m/s predicts unlimited community walking [25].

However, there is also an argument *against* the use of gait velocity as the sole metric for classification of people suffering from gait related impairments. Olney et al. [26], for example, argue that using gait velocity figures alone can neither assist in understanding the nature of gait deficits nor support direct treatment. They suggest that while gait velocity is reflective of gait performance it does not have “explicative capacity”, and is often insufficient in discriminating among post-stroke ambulators. Taylor et al. [27] noted that gait velocity as measured in the clinic can predict the walking speed of a person in the community only if it is greater than 0.8m/s. Considering that stroke survivors tend to walk more slowly than 0.8m/s, and the classification starts with 0.4 m/s for “household capability”, followed by 0.4 to 0.8 m/s for limited community capability, and more than 0.8 m/s for full community capability [25], velocity based classification systems are of limited scope.

Temporal symmetry, on the other hand, may be an additional and valuable measure that can be used when trying to classify stroke survivors into ambulation groups. Temporal symmetry is defined as the ratio of time between each leg swing and stance time of the gait cycle (see the Results section and **Fig. 1**.). Patterson et al. [28] suggest that temporal symmetry may assist in further discrimination of post-stroke ambulators; more specifically those with gait speeds less than 0.6m/s.

The main reason for widespread use of velocity data alone for patient classification is not so much its accuracy of gait capability prediction, but the ease by which it can be recorded and applied in the clinical setting. After all, all a clinician needs to record and calculate someone’s gait velocity is a stopwatch. However, small affordable technologies are increasingly available that open up the possibility of other measures that might begin to play a role in physiotherapy practice.

3 Aim of the study

As outlined above, stroke survivors are often classified in different categories based on their walking speeds. These categories are then for some purposes treated as homogenous groups. Even though this classification system has some uses within the clinic, and helps clinicians and health professionals establish a benchmark for quantifying and comparing the progress of individuals during gait rehabilitation and physiotherapy sessions, it has limited diagnostic and predictive value.

The aim of this paper is to highlight individual differences found in participants of gait related studies within otherwise homogenous groups and investigate the potential of lightweight wearable devices for exploring such differences.

4 Research approach and technology used

The present preliminary study is part of wider exploratory programme to explore the potential of new technologies, the kinds of data that they offer and their analytic use. The study involved a repeated measure design, with stroke survivors walking both with and without haptic cues. During the course of the study we talked in depth with participating stroke survivors and the physiotherapist who was directing sessions. This gave us rich qualitative data to help better understand the needs of stroke survivors and health professionals, and to help improve future design prototypes.

We also collected quantitative data from a state of the art motion capturing system. These quantitative data, the way they are analysed and the questions they raise are discussed in the sections below.

4.1 Data gathering – technologies

Data were recorded using a Qualisys Motion Capturing System, whose high spatial and temporal resolution allowed for precise motion of leg and hipbone joints to be captured. 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, were collected and filtered using a fourth–order zero lag Butterworth low-pass filters, with a 6Hz cut off frequency.

The rhythmic haptic cue was controlled using a pair of Haptic Bracelets. The Haptic Bracelets are a lightweight, wearable wireless technology developed at the Open University, able to collect motion data and provide precise haptic cueing via vibrotactiles. Generally, one bracelet is worn on each leg near the ankle. Haptic cues are delivered via high precision low-latency vibrotactiles with wide dynamic range. The metronomic delivery of cues to alternate legs is co-ordinated via a laptop, but this is being ported to smartphone for applications outside the lab.

A methodology of repeated measures ensured that participants acted as their own controls, so that any variability in the two conditions could be attributed solely to the device and the rhythmic haptic cueing, rather than to errors induced by the re-attachment of markers or to day-to-day gait variability.

4.2 Participants

Participants were included in the study if they had sustained a unilateral stroke (haemorrhagic or ischemic) more than 6 months ago; if they could walk independently for 5 minutes; and were able to walk for a minimum of 20 meters without the use of a walking aid.

Four adults were recruited (see **Table 1**). Three were males and one female, and all of the participants had a right hemiparesis. Three participants exhibited aphasia but all had recovered the ability to speak and express themselves in a coherent manner. The mean age was 58.5 (±9.47) years. The relatively wide age range does not play a significant role in gait symmetry ratios [29]. The time since the onset of stroke varied from 6-43 years. All four subjects completed a minimum of five gait trials whilst wearing normal-wear footwear. None of the participant wore splints.

Exclusion criteria included: neurological, orthopaedic, respiratory, cardiovascular or musculoskeletal problems that would prevent safe participation in testing, and any skin conditions that might be aggravated by wearing the haptic bracelet or movement analysis markers. Ethical approval for the study was gained from the Open University and the Manchester Metropolitan University ethics committee.

Table 1. Participants' demographics

	Age	Gender	Side of stroke	Year of stroke
P1	46	Female	Right	2001
P2	57	Male	Right	2004
P3	68	Male	Right	1972
P4	63	Male	Right	2009

5 Procedure

The sessions took part over three days. The first day included a familiarisation session, where participants visited the gait laboratory and were tested using the inclusion criteria by a team of expert physiotherapists. We also introduced participants to the Haptic Bracelets.

Each participant then completed a minimum of five walks on a ten-metre walkway at their natural walking pace, without haptic cueing. This allowed them to familiarise themselves with the procedure and the environment, and allowed for recording of base-line kinematic and kinetic data. Participants' preferred own pace was used for metronomic cueing, as this is considered to be the most beneficial cueing rate when used within the context of gait rehabilitation to improve symmetry [5].

On the second day, the first two participants took part in hands-on sessions in which kinematic and kinetic data was recorded without, and then with haptic cueing. On day three, this was repeated with the remaining two participants.

In general, the device was fitted to both lower limbs with the vibrotactiles fitted over the medial border of the tibia where the haptic pulse could be felt (one exception to this is noted later in the paper). The tempo of the haptic cue was calculated individually from each participant's step cycle/cadence (mean time taken from heel strike to heel strike of the same leg) during the baseline measurements on day one.

The intensity of the haptic cue was then adjusted to a comfortable level. The participants had approximately ten minutes for familiarisation with the device (either walking on the spot or sitting and marking time to the beat). Once ready, the participants were asked to 'follow the rhythm' as they performed a minimum of five walks.

All four participants were classified as community ambulators in the higher level of the classification scale (gait velocity > 0.8m/s). Being community ambulators means they are "*capable of independent mobility outside the home, including the ability to confidently negotiate uneven terrain, private venues, shopping centres and other public venues*" [30]. This relatively high walking speed put all participants in the same upper level of community ambulators. However, aspects of P2's condition merit particular consideration as follows.

P2 had symptoms of aphasia that were found to hinder him in switching attention from one leg to the other fast enough to follow the rhythmic haptic cue delivered on alternating legs. Also, his stroke incident left him with severe loss of sensitivity on his left leg. The aphasia and sensitivity loss led P2 to prefer the use of a single Haptic Bracelet strapped on his left (paretic) leg, with its vibration intensity set to the maximum. All of the other participants could readily switch attention between their limbs and their perceptual sensitivity levels were higher. These participants preferred the vibration intensity to be set at 40%.

6 Measures of gait asymmetry

For clarity in interpreting the results, it may help to briefly review key measures of gait, in particular swing and stance times, and how these are used to characterise various kinds of gait asymmetry. When walking from a standing start, one starts by swinging one leg while the other supports the weight of the body. Figure 1 shows the stages a leg passes through during a single step. The toes of one leg are lifted up (at the point labelled TO in figure 1 below), initialising the swing time of that leg. The leg then moves forward and the heel strikes the ground (labelled HS in figure 1). At this point the swing time ends and the stance time begins. Stance time ends when the toes of that foot lift off from the ground again. These stages define the swing and stance time of each leg individually.

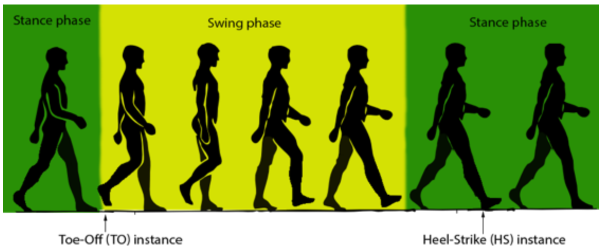

Fig. 1. The gait cycle from toe off to heel strike of one leg.

In the case of stroke survivors suffering from hemiparesis, one leg is affected more than the other. This affected leg is known as the "paretic" leg. The research literature cites several methods of calculating gait symmetry, but the ratio measure (eq. (1)) is relatively simple and easy and easy to interpret [31].

$$ratio = V_{Paretic\ limb} / V_{non-Paretic\ limb}\ . \qquad \textbf{(1)}$$

Using this formula, we can calculate the *stance time ratio*, the *swing time ratio*, the *swing-stance time ratio* and the *overall temporal symmetry ratio*.

The *stance time ratio*, as the name suggests, is the ratio of time spent during the stance phase between both limbs. If, for example, a person spent on average 0.5 a second on the paretic limb and 0.8 second on the non-paretic limb, the stance time ratio would be 0.5/0.8 = 0.625. The *swing time ratio* is calculated in the same way, but using the swing time instead. The *swing-stance time ratio*, again, as the name suggests, can be calculated by dividing the swing time by the stance time of each limb. This gives a swing-stance time ratio value *for each* leg. The *overall temporal symmetry* can then be calculated by dividing the paretic swing-stance ratio by the non-paretic swing-stance ratio value. A summary of how these terms are defined is provided in Table 2.

Table 2. Summary on how Swing time ratio, Stance time ratio, Swing-Stance time ratio and Temporal Asymmetry ratio are calculated.

	Right Leg (R)	Left Leg (L)
Example patient	Paretic	Non-Paretic
Swing Time	R_{swing_time}	L_{swing_time}
Swing Time ratio	R_{swing_time} / L_{swing_time}	
Stance Time	R_{stance_time}	L_{stance_time}
Stance Time ratio	R_{stance_time} / L_{stance_time}	
Swing / Stance Time ratio	$R_{ss\_ratio} = R_{swing\_time} / R_{stance\_time}$	$L_{ss\_ratio} = L_{swing\_time} / L_{stance\_time}$
Temporal Asymmetry ratio	$R_{ss\_ratio} / L_{ss\_ratio}$	

As previously noted, overuse of the non-paretic leg (i.e. temporal gait symmetry ratio value greater than one) exposes it to higher vertical forces, leading to joint pains, bone degeneration, and increased risk of fractures – thus gait asymmetry is something to identify and try to reduce.

7 Results

Using the measures of gait asymmetry characterised above, let us now consider the results.

Table 3. Individual Stance and Swing time ratios, with and without cueing. Stance time ratio with value less than 1.0 means that more time is spent on the non-paretic leg [28]. Swing time ratio with value greater than 1.0 means that the paretic leg takes longer to swing (leaving the body supported on only the non-paretic leg for longer).

	Stance time ratio		**Swing time ratio**	
	Haptic cue off	Haptic cue on	Haptic cue off	Haptic cue on
P1	0.76	0.74	1.58	1.64
P2	0.88	0.87	1.30	1.20
P3	0.90	0.90	1.20	1.20
P4	0.95	0.95	1.10	1.10

Table 4. Individual swing/stance time ratios and temporal asymmetry ratios, with and without cueing. The temporal asymmetry ratio was calculated by dividing the paretic by the non-paretic value for each of the two conditions. For example, for P1's Haptic off condition: 0.85/0.44 = 1.93.

		Haptic cue off		**Haptic cue on**	
	Leg	Swing - Stance ratio	Temporal Asymmetry Ratio	Swing - Stance ratio	Temporal Asymmetry Ratio
P1	Paretic	0.85	1.93	0.90	2.20
	Non-Paretic	0.44		0.41	
P2	Paretic	0.66	1.53	0.60	1.20
	Non-Paretic	0.43		0.50	
P3	Paretic	0.62	1.27	0.62	1.38
	Non-Paretic	0.49		0.45	
P4	Paretic	0.60	1.20	0.60	1.05
	Non-Paretic	0.50		0.57	

Comparing the results in Table 3, we can see that in the context of the study, the cueing appeared to improve swing time ratio for P2, but to make worse the swing time ratio for P1. No change was observed in either the stance or the swing time ratio for P3 and P4. Similarly, in Table 4, cueing appeared to improve the temporal asymmetry ratio for P2 and P4, but to make it worse for P1 and P3.

Thus, both swing time ratio (Table 3) and temporal asymmetry ratio (Table 4) measurements suggest that P2 and P4's symmetry was improved (from 1.53 to 1.20 and 1.20 to 1.05 respectively) while P1 and P3's symmetry got worse (from 1.93 to 2.20 and 1.27 to 1.38).

8 Discussion

Clearly the results raise many questions about how wearable haptics should be best used for Rhythmic Sensory Stimulation (RSS). As discussed in Section 2.2, RSS is known in general to be a successful approach to gait rehabilitation. However, the above results (and the discussion below) demonstrate that individual differences in stroke survivors need to be better understood to help determine appropriate therapy in individual cases. In this paper, we leave this wider issue for further research: for now we focus on the more restricted point that despite conventional classification methods treating our participants as broadly homogeneous, the results clearly demonstrate major individual differences. Thus, these results have implications for reconsidering classification methods. More specifically, all participants in this study were classified as community ambulators based on their baseline walking velocity (>0.8m/s). When hypothetically considering averaged kinematic data for all participants, changes for the better and worse balance out. However, looking at individual participants, the approach worked well for two participants, but not for the two others.

Interesting detail emerges when we look at the individual data of each participant. By looking at the data in Table 3, it is clear that some participants were more symmetric than others at the start of the study (as shown by uncued baselines with ratios closer to 1.0). This is even clearer from Table 4, where temporal symmetries are calculated using measurements from *both* legs. Here, the walking symmetries between participants have a wide margin of variation; varying from 1.93 to 1.20. According to these data, P1 spent almost twice the time on her affected leg, while P4 spent almost equal amount of time on both legs.

The results demonstrate that the homogeneity of the participant group as judged by conventional measures is misleading: they draw detailed attention to limitations in the use of velocity as a measure of gait performance. Such an overall conclusion is not new, but the results add considerable detail in characterising the nature and extent of the problem [13] [28].

More generally, the results were interesting and unexpected. In this small case study, Rhythmic Haptic Cueing (RHC) had little or no effect on either the stance or swing time ratio (Table 3) for participants whose ratio was good to start with (P3 and P4). However, for those who were more asymmetric without the cue (P1 and P2), the RHC did have an effect; with one getting worse, and the other improving. As regards the temporal asymmetry ratio (Table 4), the most asymmetric participant appeared to become less symmetric and the most symmetric participant appeared to approach perfect symmetry.

9 Conclusion

This study introduced rhythmic haptic cueing to a small group of stroke survivors and health professionals. The rhythmic haptic cueing was delivered through our prototype wearable device, the Haptic Bracelets, which acted as a technology probe [32]; where a new technology is placed and used in the environment it was designed for and observing how users interact with it. As part of this technology probe approach, complete motion capture data was collected and analysed, not to test any particular hypothesis, but for observing the participant's reaction to the rhythmic haptic cueing and its effect on their gait, and to help frame future research questions.

After analysing the kinematic data collected by a Qualisys Motion Capture System, we saw that for two participants (P2 and P4), rhythmic cueing had a potential benefit with their gait becoming more symmetric, whereas P1's data indicated tendencies of destabilisation (becoming more asymmetric). This raises many questions, but as a minimum brings into question the way patients are classified on their ambulation capability. In this study, within an otherwise homogenous group (based on the gait velocity test), motion capture results suggest widely different reactions to rhythm-based intervention on gait rehabilitation.

This demonstrates that group homogeneity cannot be assumed based solely on velocity. Our findings give detailed confirmation to the criticism of velocity alone as a classification metric ([13] [28]). As a result of the varying responses to rhythmic cueing revealed in this study, we propose in future work to study individual differences in sensory, motor, attention, and rhythm perception capabilities (for example, probing the ability to tap along with steady beats) so as to to correlate these with varying changes in gait symmetry elicited by rhythmic cueing.

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