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A pilot study using tactile cueing for gait rehabilitation following stroke

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Abstract. Recovery of walking function is a vital goal of post-stroke rehabilitation. Cueing using audio metronomes has been shown to improve gait, but can be impractical when interacting with others, particularly outdoors where awareness of vehicles and bicycles is essential. Audio is also unsuitable in environments with high background noise, or for those with a hearing impairment. If successful, lightweight portable tactile cueing has the potential to take the benefits of cueing out of the laboratory and into everyday life. The Haptic Bracelets are lightweight wireless devices containing a computer, accelerometers and low-latency vibrotactiles with a wide dynamic range. In this paper we review gait rehabilitation problems and existing solutions, and present an early pilot in which the Haptic Bracelets were applied to post-stroke gait rehabilitation. Tactile cueing during walking was well received in the pilot, and analysis of motion capture data showed immediate improvements in gait.

Keywords: Haptic Bracelets, stroke, gait rehabilitation, tactile metronome, haptic metronome, Parkinson's disease, fall prevention, walking, hemiparesis.

1 Introduction

The Haptic Bracelets are devices for tactile communication and co-ordination, originally designed and built by the Open University for musical purposes, such as learning and teaching multi-limbed rhythms. This paper considers an early pilot study in which the Haptic Bracelets were applied to gait rehabilitation following stroke.

2 Gait rehabilitation following stroke

2.1 Characteristics of post-stroke gait

According to the World Health Organisation, approximately 15 million people experience a stroke each year. In the majority of cases, stroke results in some degree of one-sided muscle weakness or hemiparesis. Impairment of gait following a stroke can have a major impact on an individual's life [1], and can impose substantial costs on health and social services [2]. Although the majority of stroke patients eventually recover an independent gait, many never regain a level of walking that allows common daily activities [3]. Thus, improvement of gait is a major goal of post stroke rehabilitation.

Walking after a stroke is characterized by decreased speed [4], increased variability [5], and spatial and/or temporal asymmetry [6]. As a result, the non-paretic limb is regularly exposed to higher vertical forces [7]. Over time, this can lead to further problems, such as joint pain [8] and degeneration [9]. An asymmetrical gait is associated with worse performance on clinical balance tests [10] and therefore may be linked to the increased risk of falling observed after stroke. Understanding and rehabilitating these features of hemiparetic gait is of vital importance, since walking affords a high level of independence, and thus a better quality of life for stroke survivors in general [11].

2.2 Existing gait rehabilitation approaches

Hollands et al [12] presented a systematic review of gait rehabilitation techniques after stroke, and identified external rhythmic cueing as a technique showing great promise for walking rehabilitation. Immediate effects of an auditory metronome have been reported, with chronic stroke patients able to synchronise to a metronome during treadmill walking [13]. Improvements in spatial [14] and temporal symmetry [15] and step time variability [16] were observed with auditory pacing, as was the ability to make gait adjustments in response to changes in the cue [17]. Auditory cueing has also been used in gait rehabilitation programmes, with significantly greater improvements in walking speed and stride length with auditory cueing compared to conventional gait training [18] and Bobath training [19].

Other modalities appear to have considerable promise for external cueing. Therapists routinely use touch to help stabilise patients and reduce postural sway. Visual spatial cues in the form of projected stepping-stones have also been used, and perturbation of the spatial phase of these cues shows promise [20]. However, these approaches can be intrusive, or can require laboratory installations, or both, whereas touch can be covert and more practical to apply in everyday life. It is known [21] that tactile cues can lead to an increase in stride length, without disrupting the natural gait rhythm in healthy participants.

3 The Haptic Bracelets

The Haptic Bracelets, designed and built at the Open University, are self-contained lightweight devices for wrists and ankles [22]. Each bracelet contains a computer, Wi-Fi chip, accelerometers and powerful, low-latency vibrotactiles with a wide dynamic range. The bracelets were originally designed for musical purposes, to be worn in sets of four (on each wrist and each ankle) – though, as in the present case, wearing fewer also has many useful applications. Bracelets can be coordinated and communicate together via laptop or smart phone. It is possible for sets worn by two or more people, whether co-located or remote, to be used for synchronization or communication in various ways. Synchronised use by two wearers is a feature of one of the therapeutic applications outlined below. The vibrotactiles are very low latency, and can be felt 6 milliseconds after activation. The wireless Haptic Bracelets evolved out of the earlier Haptic Drum Kit [23] and our wider investigations of haptic technologies [24].

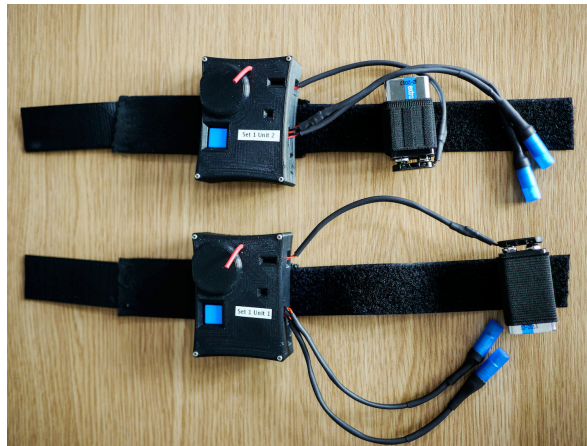


Figure 1. Two Haptic Bracelets.

In figure 1, the vibrotactiles (two per unit) are visible as blue caps at the tip of the black leads. The third black lead on each unit connects to an external battery pack. Separation of the vibrotactiles from the main unit allows flexible placement of the vibrotactiles to suit individual wearers. This feature also helps to avoid feedback between vibrotactiles and accelerometers in applications that combine two way haptic communication. Given that parts of the ankles are generally less sensitive than the wrists, this flexibility of placement is also useful when bracelets are worn on the ankles. The vibrotactiles are typically tucked under the strapping in positions to suit the individual wearer.

The wide dynamic range of the vibrotactiles means that while they can be set to as vibrate gently as preferred on wrists, they can also be adjusted to a higher level if strapped outside socks or trousers. In early design trials (section 4) haptic cues could be clearly felt even when strapped on the outside of knee length boots. This is particu-

larly useful, since the ease of perceiving cues on hemiparetic limbs can vary considerably amongst stroke survivors.

Also visible in figure 1 are a multipurpose rotary control and a multi-purpose button. In the present applications these may be used to set the level of the vibrotactiles, and to switch them off. These and other functions can also be controlled where appropriate from an external computer.

3.1 Modes of use of the Haptic Bracelets in gait rehabilitation

We are currently prototyping three principal modes of tactile cueing in gait rehabilitation. The simplest mode constitutes a portable tactile metronome (the focus of this paper). If tactile cueing demonstrates similar benefits to auditory cueing [14,15,16,17] this approach would offer the benefit of being usable in a wide range of contexts, for example in the street, while avoiding the inconvenience and dangers associated with wearing earphones when awareness of motor vehicles, bicycles and other pedestrians is needed. The bracelets can at the same time collect gait data via the in-built accelerometers for live streaming via Wi-Fi, or for storage and later analysis. When used as a tactile metronome, one can be worn on each leg, with each bracelet cueing the leg on which it is worn. Alternatively, where preferred, a single bracelet can be worn on one wrist, with cues on the single wrist cueing both left and right footfalls. A second mode of use is flexible interactive pacing, with the aid of a carer, therapist or partner. The motivation in this second mode of use is that in situations where stumbles, environmental obstacles, changing slopes or other irregularities might make it impractical for the participant to keep in phase with a fixed beat, a partner wearing a communicating pair of bracelets could flexibly beat an appropriate pulse, either by beating with their hands, or simply by walking. The third mode of use is autonomous gait monitoring. In this mode, aimed at post-care, a pair of bracelets worn on the ankles continually monitor gait speed or gait asymmetry when the participant is walking, and give gentle tactile metronomic guidance when speed or symmetry falls below a pre-chosen limits. Prototype versions of all three of these applications have been implemented and are being piloted with stroke survivors. In this paper we focus on the first application alone.

4 Preliminary views of practitioners

As part of the system design process, before conducting a pilot test with a stroke survivor, we carried out participative demonstrations of the bracelets with two distinct meetings of physiotherapists with interests in neurology. Firstly, a brief invited talk, and participative demo, of the Haptic Bracelets was presented to a meeting of some fifty members of the professional Association of Chartered Physiotherapists with Interests in Neurology (ACPIN). This group (<http://www.acpin.net/>) has special interests in the neuro-rehabilitation of conditions such as Stroke, Parkinson's disease (PD), Ataxia and Head injury. Three potential applications of the Haptic Bracelets in rehabilitation were outlined as noted above: the tactile metronome, flexible therapist-

driven tactile cueing, and post-care live gait monitoring and feedback. The first two of these applications were demonstrated. In order to inform design work, as well as collecting detailed comments, survey feedback from some fifty ACPIN participants was evaluated to find out initial general views on the likely relative value of the three approaches.

Table 1. General views of meeting of Physiotherapists with Interests in Neurology

Proposition	Agree	Agree Strongly
The tactile metronome has the potential to influence practice	89%	55%
Live monitoring and feedback on gait symmetry has the potential to influence practice	83%	50%
Flexible tactile cueing has the potential to influence practice	93%	27%

Comments from members included:

'Great for Parkinson's disease - Cueing to enable stepping - PD patients tend to "freeze" and use visual/audio cueing to trigger stepping - tactile cueing could assist this.'

'Stroke patients tend to have unequal stride length - the use of a metronome to encourage equal stepping by patients.'

'Use of feedback would assist therapists analysing gait and for patients to see their gait pattern.'

Secondly, a presentation and participatory workshop was run for some seventeen physiotherapists from the Wye Valley NHS Trust. The workshop was part of a research day organised by a research facilitator from the West Midlands Stroke Research Network (http://www.crncc.nihr.ac.uk/about_us/stroke_research_network/in_your_area/west_midlands). The participatory workshop examined the pros and cons of cueing the gait or arm movements of patients with conditions such as Stroke, Parkinson's disease, Cerebral Palsy, Head injury, Ataxia, and others, using the Haptic Bracelets, as compared with other approaches. All participants were able to try out the Haptic Bracelets. Situations were identified where the Haptic Bracelets are not suitable for therapy (e.g. rehabilitation of grasp and reach, and in some Parkinson's disease cases where spasticity might be increased). Again, in order to inform design refinements, as well as collecting detailed comments, survey feedback from participants was evaluated to gain an impression of practitioners' initial views on the likely relative value of the three approaches.

Table 2. General views of physiotherapists at participative workshop

Proposition	Agree	Agree Strongly
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The tactile metronome has the potential to influence practice	91%	50%
Live monitoring and feedback on gait symmetry has the potential to influence practice	91%	50%
Flexible tactile cueing has the potential to influence practice	49%	33%

Comments from attendees included:

'Maybe not appropriate for musculoskeletal patients with gait re-training in higher levels such as sporting injuries.'

'May help with children and developmental problems, for tapping etc.'

'Consider how therapists use, sensory input to facilitate neurological rehabilitation & the effects sensory stimulation can have on aspects such as tone/spasticity/muscle activation.'

5 Pilot Study with stroke survivor

5.1 Aims

The preliminary pilot study investigated the immediate effects of tactile cueing during walking with the Haptic Bracelets in a participant with hemiparesis.

5.2 Method

We recruited a female participant with chronic right hemiparesis (aged 69 years, height 1.66m, mass 63.8kg, Fugl-Meyer lower limb assessment = 29, 12 years post-stroke), who provided written informed consent. Testing took place in the large (17 x 12 x 4.5 metres) gait laboratory in the Motion and Performance Centre at the University of Worcester. Whole body motion data were collected at 60Hz using a fifteen camera Mcam2 Vicon system (Vicon Peak, Oxford Metrics Ltd., UK), according to standard clinical gait analysis procedures. The participant wore a single bracelet on her left (non-paretic) wrist (figure 2).



Figure 2. Preparing for the pilot study

During pre-test, the participant performed 5 standard gait trials for baseline measures. Her cadence was averaged from these trials to generate the inter-response interval for the tactile cue. The participant had a 5-minute familiarization period of walking to the tactile cue. She was instructed to time her footfalls to the cue. This was followed by 5 walking trials with steps cued by the tactile device worn on her left wrist (Figure 3), followed by a final 5 un-cued walking trials. Seated rest was taken between each walking condition to minimize fatigue effects.

Marker position data were filtered using the Woltring cross-validity quantic spline routine [25]. Step time asymmetry was determined using a step time ratio where the paretic step time was divided by the non-paretic step time. Similarly, step length asymmetry was quantified using a step length ratio where the paretic step length was divided by the non-paretic step length [26]. Sagittal hip, knee and ankle angles were calculated from the kinematic marker data using the Plug-in Gait model (Vicon Peak, Oxford Metrics Ltd., UK) and reported in degrees. Joint angles were segmented into discrete gait cycles and normalized to 0-100% of the gait cycle. Minimal detectable change values for gait variables in a within-session setting were used to identify functional differences between conditions [27,28].



Figure 3. Tactile cued walking of a stroke survivor. As well as wearing a haptic bracelet on the paretic (right arm), the participant is wearing optical markers on the body for motion tracking.

5.3 Results

The participant's normal walking speed was $0.82\text{m}\cdot\text{s}^{-1}$, increasing to $0.85\text{ m}\cdot\text{s}^{-1}$ when cued by the tactile bracelet. She displayed a mild level of temporal asymmetry at baseline, and a normal level of spatial symmetry. Her step length increased with the tactile cue, and the 3cm increase for the paretic step was above the minimum detectable change threshold.

Analysis of the lower limb joint angle data (see table 3) showed that the participant's paretic lower limb joint motion was reduced in all conditions compared to the laboratory's normal database. Her paretic, hip angle at toe off (figure 4) peak knee flexion during swing (figure 5) and ankle range of motion (figure 6) increased above the minimum detectable change threshold when cued with the tactile device compared to her baseline values.

The participant reported that she felt the tactile bracelet helped to generate an even walking pace, and that she felt she was using her hip more to swing her leg through straighter. Comments by the participant included:

"I must say its makes you stand up straighter"

"When I stand up straight my hips move better and I walk more smoothly and it's easier."

"I think it might help to remind you that you should be walking in this way"

"it does help.... this helps me to walk in time. It's just sort of having an even pace ... which helps me stand up straight and walk properly."

Table 3 Gait variables in the three walking conditions

	Baseline	Cued	Post-cueing
Walking speed ($m.s^{-1}$)	0.82	0.85	0.81
Non-paretic step time (s)	0.52	0.54	0.52
Paretic step time (s)	0.63	0.63	0.63
Step time ratio	1.21	1.17	1.21
Non-paretic step length (m)	0.47	0.48	0.47
Paretic step length (m)	0.46	0.49	0.45
Step length ratio	0.98	1.02	0.96
Paretic hip angle at toe off ($^{\circ}$)	-5.8	-8.3	-7.3
Peak paretic knee flexion during swing ($^{\circ}$)	32.3	39.8	37.8
Paretic ankle range of motion ($^{\circ}$)	24.5	27.6	25.1

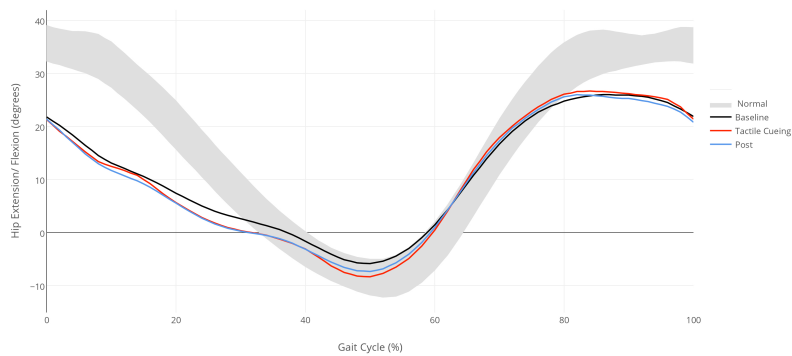


Figure 4. Paretic hip angles across the gait cycle. The grey band shows the normal range; the black trace is baseline, the red trace is with tactile cueing and the blue trace is post cueing.

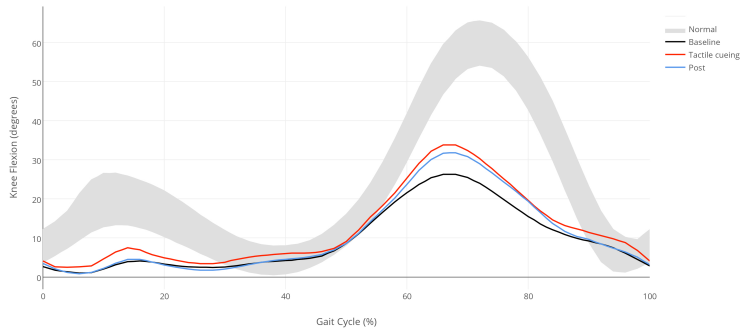


Figure 5. Paretic Knee angles across the gait cycle.

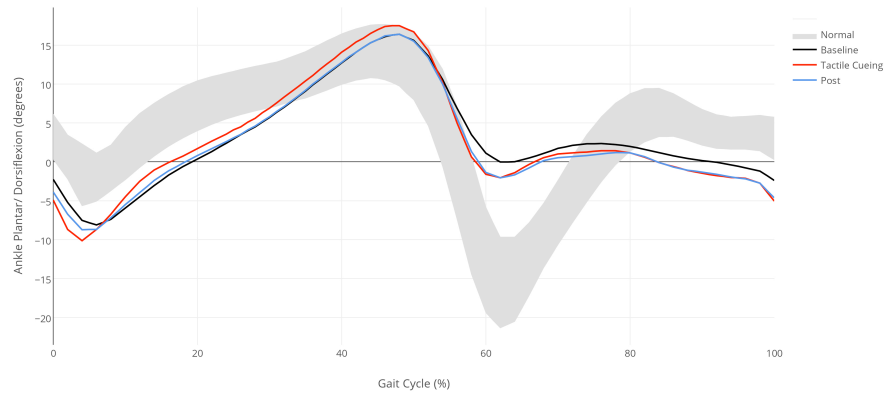


Figure 6. Paretic ankle angles across the gait cycle.

5.4 Discussion

The aim of this single case pilot study was to investigate any immediate effects on walking in post-stroke hemiparesis, and to gain user feedback from a participant. Walking speed and step length were both slightly increased in the cued walking condition. The reduction in temporal asymmetry observed when using the tactile cue is of a slightly lower magnitude than previously reported for auditory cueing when treadmill walking [18] or stepping in place [19]. This may be due to the participant in the current study only displaying mild temporal asymmetry, and future research with

a participant group is needed to determine whether asymmetry improvements with a tactile cue are similar to those observed with an auditory cue.

The increase in hip extension at toe off for both tactile cueing and post-cueing conditions from baseline were above the minimum detectable change value for a stroke population. This suggests the increases are clinically meaningful, and supports the participant's views that the tactile cue helped her use her hip. An increase in hip extension is associated with a longer step length and an increased potential to flex the knee during swing [29].

A reduction in peak knee flexion during walking is common after stroke [30], and is associated with compensatory measures to increase toe clearance as the leg is swung through in this phase of the gait cycle [7]. Even a small angular improvement at the knee reduces the risk of tripping and falling [31]. The 7.5° and 5.5° increases in knee flexion for the cued condition and immediately post-cueing are not only clinically meaningful for walking function, but could also have benefits for reducing fall risk after stroke. Further research is needed to determine whether these improvements can be sustained.

Tactile cueing during walking was viewed positively by the participant in this study, and produced immediate improvements at the hip, knee and ankle on the paretic limb. This single case study indicates that a larger study investigating tactile cueing in hemiparetic gait is warranted.

6 Conclusions

Recovery of walking function is a paramount goal of rehabilitation after stroke. Existing therapies using audio metronomes have been reported to have valuable immediate effects, but gait asymmetry can be very resistant to long term improvement [21]. Audio cueing can be unsuitable outside the lab, due to dangers associated with earphone use near to motor vehicles, bicycles or even other pedestrians. Tactile cueing has potential to offer similar benefits to an auditory cue. In portable form, this approach could be used outside the lab for long periods without the potential problems associated with audio cueing. We have outlined three potential applications of the Haptic Bracelets in gait rehabilitation post-stroke, and have reported on an initial pilot study with an individual with post-stroke hemiparesis. The preliminary data suggests that a tactile device may have immediate benefits for walking in individuals post-stroke and warrants further investigation.

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REFERENCES

1. Belda-Lois, Juan-Manuel, et al. "Rehabilitation of gait after stroke: a review towards a top-down approach." *Journal of neuroengineering and rehabilitation* 8.1 (2011): 66.
2. Evers SM, Struijs JN, Ament AJ, van Genugten ML, Jager JC, van den Bos GA: International comparison of stroke cost studies. *Stroke* 2004, 35:1209-1215.
3. Flansbjerg UB, Holmbäck AM, Downham D, Patten C, Lexell J: Reliability of gait performance tests in men and women with hemiparesis after stroke. *Journal of Rehabilitation Medicine* 2005, 37:75-82.
4. S. J. Olney and C. Richards, "Hemiparetic gait following stroke. Part I: characteristics," *Gait & Posture*, vol. 4, no. 2, pp. 136–148, 1996.
5. C.K. Balasubramanian, R.R. Neptune and SA Kautz, "Variability in spatiotemporal step characteristics and its relationship to walking performance post-stroke", *Gait & Posture*, vol. 29, pp. 408-414, 2009
6. G. Chen, C. Patten, D. H. Kothari, and F. E. Zajac, "Gait differences between individuals with post-stroke hemiparesis and non-disabled controls at matched speeds," *Gait & Posture*, vol. 22, no. 1, pp. 51–56, 2005.
7. Kim, C. Maria, and Janice J. Eng. "The relationship of lower-extremity muscle torque to locomotor performance in people with stroke." *Physical Therapy* 83.1 (2003): 49-57.
8. D. C. Norvell, J. M. Czerniecki, G. E. Reiber, C. Maynard, J. A. Pecoraro, and N. S. Weiss, "The prevalence of knee pain and symptomatic knee osteoarthritis among veteran traumatic amputees and nonamputees," *Archives of Physical Medicine and Rehabilitation*, vol. 86, no. 3, pp. 487–493, 2005.
9. L. Nolan, A. Wit, K. Dudziński, A. Lees, M. Lake, and M. Wychowanski, "Adjustments in gait symmetry with walking speed in trans-femoral and trans-tibial amputees," *Gait & Posture*, vol. 17, pp. 142–151, 2003.
10. M. D. Lewek, C. E. Bradley, C. J. Wutzke, and S. M. Zinder, "The relationship between spatiotemporal gait asymmetry and balance in individuals with chronic stroke," *Journal of Applied Biomechanics*. In press.
11. Richards, Carol L., et al. "Task-specific physical therapy for optimization of gait recovery in acute stroke patients." *Archives of physical medicine and rehabilitation* 74.6 (1993): 612-620.
12. K.L. Hollands, T.A. Pelton, S.F. Tyson, M.A. Hollands and P.M. van Vliet, "Interventions for coordination of walking following stroke: systematic review", *Gait & Posture*, vol. 35, no.3, pp. 349-359, 2012.
13. M. Roerdink, C. J. C. Lamothe, G. Kwakkel, P. C. W. van Wieringen, and P. J. Beek, "Gait coordination after stroke: benefits of acoustically paced treadmill walking," *Physical Therapy*, vol. 87, no. 8, pp. 1009–1022, 2007.
14. Prassas, Spiros, et al. "Effect of auditory rhythmic cuing on gait kinematic parameters of stroke patients." *Gait & Posture* 6.3 (1997): 218-223.
15. M. Roerdink, C. J. C. Lamothe, G. Kwakkel, P. C. W. van Wieringen, and P. J. Beek, "Gait coordination after stroke: benefits of acoustically paced treadmill walking," *Physical Therapy*, vol. 87, no. 8, pp. 1009–1022, 2007.
16. R.L. Wright, A. Masood, E.S. MacCormac, D. Pratt, C.M. Sackley and A.M. Wing, "Metronome-cued stepping in place after hemiparetic stroke: Comparison of a one- and two-tone beat" *ISRN Rehabilitation*, vol. 2013, no. 157410, pp.1-5, 2013.
17. T. A. Pelton, L. Johannsen, H. Y. Chen, and A. M. Wing, "Hemiparetic stepping to the beat: asymmetric response to metronome phase shift during treadmill gait," *Neurorehabilitation and Neural Repair*, vol. 24, no. 5, pp. 428–434, 2010.

18. Thaut, Michael H., G. C. McIntosh, and R. R. Rice. "Rhythmic facilitation of gait training in hemiparetic stroke rehabilitation." *Journal of the neurological sciences* 151.2 (1997): 207-212.
19. M. H. Thaut, A. K. Leins, R. R. Rice et al., "Rhythmic auditory stimulation improves gait more than NDT/Bobath training in near-ambulatory patients early poststroke: a single-blind, randomized trial," *Neurorehabilitation and Neural Repair*, vol. 21, no. 5, pp. 455–459, 2007.
20. Bank, Paulina JM, Melvyn Roerdink, and C. E. Peper. "Comparing the efficacy of metronome beeps and stepping stones to adjust gait: steps to follow!" *Experimental brain research* 209.2 (2011): 159-169.
21. Sejdić, Ervin, et al. "The effects of rhythmic sensory cues on the temporal dynamics of human gait." *PloS one* 7.8 (2012): e43104.
22. Bouwer, A; Holland, S and Dagleish, M (2013). The Haptic Bracelets: learning multi-limb rhythm skills from haptic stimuli while reading. In: Holland, S; Wilkie, K; Mulholland, P and Seago, A Eds. *Music and Human-Computer Interaction. Cultural Computing*. London: Springer.
23. Holland,S., Bouwer,A, Dagleish,M. and Hurtig, T. (2010) Feeling the Beat where it counts: Fostering Multi-limb Rhythm Skills with the Haptic Drum Kit. In *Proceedings of TEI 2010 Boston Cambridge Mass.* Oro ID 18.
24. Bird, Jon; Holland, Simon; Marshall, Paul; Rogers, Yvonne and Clark, Andy (2008). Feel the force: Using tactile technologies to investigate the extended mind. In: *Proceedings of Devices that Alter Perception*, 21 September 2008, Seoul, Korea.
25. Woltring HJ. A Fortran Package for Generalized, Cross-Validatory Spline Smoothing and Differentiation. *Advances in Engineering Software and Workstations* 1986 April;8(2):104-13
26. Balasubramanian CK, Bowden MG, Neptune RR, Kautz SA. Relationship Between Step Length Asymmetry and Walking Performance in Subjects With Chronic Hemiparesis. *Arch Phys Med Rehabil* 2007 January 1;88(1):43-9.
27. T.M. Kesar, S.A. Binder-Macleod, G.E. Hicks and D.C. Reisman, "Minimal detectable change for gait variables collected during treadmill walking in individuals post-stroke", *Gait & Posture*, vol. 33, pp. 314-317, 2011.
28. J.M. Wilken, K.M. Rodriguez, M. Brawner and B.J. Darter, "Reliability and minimal detectable change values for gait kinematics and kinetics in healthy adults", *Gait & Posture*, vol. 35, pp. 301-307, 2012.
29. George-Reichley DG, Higginson JS. Potential Muscle Function During the Swing Phase of Stroke Gait. *Journal of Applied Biomechanics* 2010 May;26(2):180-7.
30. Olney SJ, Griffin MP, McBride ID. Temporal, Kinematic, and Kinetic Variables Related to Gait Speed in Subjects With Hemiplegia: A Regression Approach. *PHYS THER* 1994 September 1;74(9):872-85.
31. Levinger P, Lai DTH, Menz HB, Morrow AD, Feller JA, Bartlett JR, Bergman NR, Begg R. Swing limb mechanics and minimum toe clearance in people with knee osteoarthritis. *Gait & Posture* 2012 February; 35(2):277-81.
32. Simon Holland, Rachel L.Wright, Alan Wing, Thomas Crevoisier, Oliver Hödl, Maxime Canelli (2014) A Gait Rehabilitation pilot study using tactile cueing following Hemiparetic Stroke. *REHAB* 2014. European Union Digital Library. <http://dx.doi.org/10.4108/icst.pervasivehealth.2014.255357>