Step into the future: Foot augmented gait entrainment for motor re-learning

Gunarajulu Renganathan*
gunarajulu.renganathan@aist.go.jp
National Institute of Advanced Industrial Science and Technology
Tokyo, Japan
Hiroshima University
Hiroshima, Japan

Mitsunori Tada
m.tada@aist.go.jp
National Institute of Advanced Industrial Science and Technology
Tokyo, Japan

Yuichi Kurita
ykurita@hiroshima-u.ac.jp
Hiroshima University
Hiroshima, Japan

Abstract

Gait guidance and rehabilitation have received significant attention recently, especially for those with movement disorders. Effective gait rehabilitation requires concurrent spatiotemporal guiding, since alterations in one gait parameter may unintentionally affect others. This work discusses the development of an interactive gait support system that incorporates foot sensors (in-shoe IMU) to monitor gait characteristics. The technology utilizes a pneumatic gel muscles (PGM) actuator to provide real-time support according to a mutual entrainment concept. Through interactive synchronization, participants progressively adjust their gait to match the system, resulting in adaptive alterations to their step patterns. Consequently, the method enables the (re)emergence of a 1/f fluctuation pattern in human movement, a fundamental attribute of natural locomotion. Interactive assistance facilitates the correction of gait irregularities while enhancing dynamic stability and flexibility in human mobility. The suggested approach may improve rehabilitation results and advance more effective gait treatment methods.

CCS Concepts

• **Human-centered computing** → *Collaborative interaction.*

Keywords

Entrainment, Pneumatic gel muscle, Foot augmentation, In-shoe IMU, Assistive device, Motor re-learning

ACM Reference Format:
Gunarajulu Renganathan, Mitsunori Tada, and Yuichi Kurita. 2025. Step into the future: Foot augmented gait entrainment for motor re-learning. In *Proceedings of XXX (CHI'25)*. ACM, New York, NY, USA, 3 pages. https://doi.org/XXXXXXX.XXXXXXX

ACM ISBN 978-1-4503-XXXX-X/2018/06
https://doi.org/XXXXXXX.XXXXXXX

1 Introduction

1.1 Movement function disorder demographics

Japan's disability statistics state that 7.6% of the total population is affected by various types of disability. Of these, 45% are physical disabilities caused by stroke, muscle weakness, and fracture/falls [8]. Individuals with neurodegenerative disorders experience challenges in generating natural rhythm and timing of repeated movements, leading to atypical gait. Gait impairment accompanied by lower extremity motor dysfunction compromises locomotion and hinders reintegration into society [1]. In recent years, behavioural treatment incorporating interactive co-creation rehabilitation has been extensively utilized to enhance movement function disorders [11]. Also, the foot functions are recognized as an analogy for the internal neural circuits in the field of rehabilitation. Since its sensorimotor functionalities can be tuned to re-establish natural rhythmic movements [3]. By leveraging targeted interventions that engage foot dynamics, it may be possible to restore natural synchronization and improve gait patterns [5].

1.2 State of art

The study by Freeman et al. [1933] suggests that the problem with abnormal gait is due to the disruption of the projection path entering the spinal cord through the basal ganglia and the brain stem, which interferes with repeated rhythmic movements [2]. However, the improvement is evident with features such as increased stride length, velocity, and decreased double support time reinforced when the constant rhythmic stimulus was used [4]. The external auditory rhythms compensated for the deficit in internal rhythm generation to entrain and bridge a neural connection between the sensorimotor and auditory areas. The enhancement of timing remains in the nearer term after the removal of auditory cues, indicating that external rhythms can stabilize internal rhythm-generating networks. Hove et al. [2012] demonstrated that the distribution of stride time in healthy walking has a 1/f structure. In addition, decreased fractal scaling is associated with pathological gait [6]. A recent study [7] used an interactive Walk-mate system to improve gait in Parkinson's patients. Foot contact times were used as rhythmic auditory stimulation, resulting in greater improvements in walking patterns.

While auditory-based interactions may facilitate patient entrainment during ambulation, the enhancement of functional mobility remains unexamined. Therefore, the neuro-behavioral manifestations may be associated with external limitations and perturbations from soft wearable assistive devices. This study aims to discuss

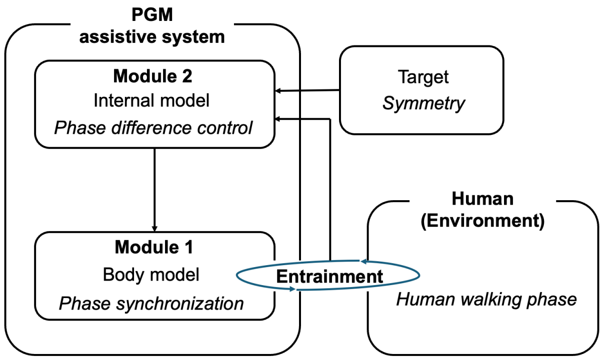

Figure 1: Mutual entrainment/Coherency model

Figure 2: PGM suit with foot augmented gait entrainment system

the aforementioned rationale. The intervention aimed at restoring bimanual coordination of lower limb patterns encompasses two parameters: initiation time and movement time [10]. Given that the lower extremity demonstrates a tendency to exhibit the characteristics of central nervous system coordination, we contend that stroke-induced patterns may be adjustable; hence, symmetrical walking might be achievable with natural frequency tuning and coupling. Soft PGMs are optimal for support in both research and rehabilitation training [9].

2 Connection between foot and human augmentation

2.1 Concept of mutual entrainment

The rhythm generator model in the virtual robot (PGM assistive system) exhibits a hierarchical structure as shown in Fig. 1. At its core, the system is designed to achieve mutual entrainment between human footsteps and the virtual robot system. Module 1 facilitates this entrainment by synchronizing the step timing of the user with the system's internal rhythm. Furthermore, non-linear phase oscillators in Module 1 mimic central pattern generators (CPGs) which play a key role in human locomotion.

Module 2 subsequently enhances this synchronization process by controlling the phase difference (temporal shift) between the sensory input, namely the subject's foot contact timing, and the output of the pneumatic gel muscle actuator (PGM). Module 2 mitigates asymmetry between the two legs by ensuring that assistance is delivered at the desired phase. Furthermore, the feedback control mechanisms in this module rectify timing disparities between input and output signals within Module 1, so maintaining consistent rhythm regulation.

The significance of the rhythm generator paradigm is further supported by evidence suggesting that human locomotor behaviors are hierarchically regulated through spinal CPG-dependent rhythm modulation, along with cerebellar and brainstem feedback control mechanisms.

2.2 Soft wearable PGM actuator for mobility assistance

PGMs are compliant, soft, wearable actuators capable of producing 70N at maximum elongation length under 0.3 MPa air pressure. Pathological gait patterns, such as hemiplegia, are often characterized by significant muscle weakness in the hip joint. To address this, soft and wearable PGM suits would be an option to effectively utilize the foot contact timing detected by an IMU sensor placed in the middle of the footwear. Two sets of PGM were placed over the thigh muscles to assist in the swing phase of the gait cycle as shown in Fig. 2. This repetitive assistance training aims to re-establish the neural connection between the brain and the lower limb muscles, facilitating motor recovery. The foot-flat phase of the ipsilateral leg occurs at 10% of the gait cycle, while the contralateral leg enters the swing phase at approximately 60% of the gait cycle. During the phase as target, the assistance is applied to the contralateral leg to reduce gait asymmetry. During gait with PGM assistance, stride intervals of both legs drew closer to each other through mutual entrainment. Simultaneously, the phase difference between the subject and the virtual robot converged to the target value set to 0 rad. The phenomenon of entrainment has the potential to stabilize the user and improve coordination. Based on the stride interval timing, we could visualize the target phase difference that can be precisely controlled in mutual synchronization between human and virtual robot (PGM).

2.3 Potential possibilites for non-invasive neuromodulation

The coalition of multiple constraints, such as neural, muscular, spatial, temporal, and attentional, may interact with coupling at both the neural and behavioural levels. This coupling strength can be leveraged as a co-creative rehabilitation tool, interlinked to bridge or tune the natural frequency through soft PGM assistance. This process can be understood as a spontaneous coordination re-learning paradigm, where movement patterns are gradually reorganized.

By augmenting foot-based spatial and temporal characteristics, neuro-behavioural modulation, combined with muscular assistance, may help train cross link pathways to the central nervous system. This approach holds promise for enhancing movement coordination and restoring functional gait patterns in individuals with motor impairments.

3 Discussion keypoints

The subsequent areas of discussion aim to advance human-computer interaction (HCI) within the realm of rehabilitation, particularly in enhancing foot-based feedback for improved motor recovery and movement coordination.

(1) In HCI, how can foot-based feedback be refined to improve the user experience while minimizing cognitive overload?
(2) What are the principal factors to consider when designing tactile or rhythmic feedback mechanisms via foot augmentation to ensure an intuitive and natural sensation during walking or rehabilitation exercises?

4 Conclusion

This conceptual framework and design modalities show the ability of soft PGM support to synchronize human gait through mutual entrainment, which presents an innovative method of neurorehabilitation. The technology combines foot-based input and rhythmic modulation to facilitate the re-learning of coordinated movement patterns, enabling intuitive, non-invasive neuromodulation techniques.

Acknowledgments

This work was supported by Council for Science, Technology and Innovation, "Cross-ministerial Strategic Innovation Promotion Program (SIP), Development of foundational technologies and rules for expansion of the virtual economy" (JPJ012495). (Funding agency: NEDO). This work was also supported by JST SPRING, Grant Number JPMJSP2132.

References

[1] Nadia Bolognini, Cristina Russo, and Dylan J Edwards. 2016. The sensory side of post-stroke motor rehabilitation. *Restorative neurology and neuroscience* 34, 4 (2016), 571–586.
[2] GL Freeman. 1933. The facilitative and inhibitory effects of muscular tension upon performance. *The American Journal of Psychology* 45, 1 (1933), 17–52.
[3] Scott H Frey, Leonardo Fogassi, Scott Grafton, Nathalie Picard, John C Rothwell, Nicolas Schweighofer, Maurizio Corbetta, and Susan M Fitzpatrick. 2011. Neurological principles and rehabilitation of action disorders: computation, anatomy, and physiology (CAP) model. *Neurorehabilitation and neural repair* 25, 5_suppl (2011), 6S–20S.
[4] Jeffrey M Hausdorff, Justine Lowenthal, Talia Herman, Leor Gruendlinger, Chava Peretz, and Nir Giladi. 2007. Rhythmic auditory stimulation modulates gait variability in Parkinson's disease. *European Journal of Neuroscience* 26, 8 (2007), 2369–2375.
[5] Cornelia Hensel, Ute Eck, Merkur Alimusaj, Rudolf Kaschuba, Anne von Reumont, Rüdiger Rupp, and Eva-Maria Schmidt. 2017. Neurorehabilitation: strategies of lower extremities restoration. *Neurological aspects of spinal cord injury* (2017), 649–688.
[6] Michael J Hove, Kazuki Suzuki, Hirotaka Uchitomi, Satoshi Orimo, and Yoshihiro Miyake. 2012. Interactive rhythmic auditory stimulation reinstates natural 1/f timing in gait of Parkinson's patients. *PloS one* 7, 3 (2012), e32600.
[7] Dane AL Miller, Hirotaka Uchitomi, and Yoshihiro Miyake. 2024. Effects of Gradual Spatial and Temporal Cues Provided by Synchronized Walking Avatar on Elderly Gait. *Applied Sciences* 14, 18 (2024), 8374.
[8] Labour Ministry of Health and Welfare. 2020. *Summary Report of Comprehensive Survey of Living Conditions 2019.* Retrieved January 2, 2025 from https://www.mhlw.go.jp/english/database/db-hss/dl/report_gaikyo_2019.pdf
[9] Priyanka Ramasamy, Gunarajulu Renganathan, and Yuichi Kurita. 2023. Force Feedback-Based Gamification: Performance Validation of Squat Exergame Using Pneumatic Gel Muscles and Dynamic Difficulty Adjustment. *IEEE Robotics and Automation Letters* (2023).
[10] Rita Sleimen-Malkoun, Jean-Jacques Temprado, Laurent Thefenne, and Eric Berton. 2011. Bimanual training in stroke: How do coupling and symmetry-breaking matter? *BMC neurology* 11 (2011), 1–9.
[11] Hirotaka Uchitomi, Ken-ichiro Ogawa, Satoshi Orimo, Yoshiaki Wada, and Yoshihiro Miyake. 2016. Effect of interpersonal interaction on festinating gait rehabilitation in patients with Parkinson's disease. *PLoS One* 11, 6 (2016), e0155540.

Received 20 February 2007; revised 12 March 2009; accepted 5 June 2009