# Using visual stimuli to enhance gait control

By: Christopher K. Rhea, Nikita A. Kuznetsov

Rhea, C.K. & Kuznetsov, N.A. (2017). Using visual stimuli to enhance gait control. Journal of Vestibular Research, 27(1), 7-16.



**The final publication is available at IOS Press through** http://dx.doi.org/10.3233/VES-170602

**Abstract:**

Gait control challenges commonly coincide with vestibular dysfunction and there is a long history in using balance and gait activities to enhance functional mobility in this population. While much has been learned using traditional rehabilitation exercises, there is a new line of research emerging that is using visual stimuli in a very specific way to enhance gait control. For example, avatars can be created in an individualized manner to incorporate specific gait characteristics. The avatar could then be used as a visual stimulus to which the patient can synchronize their own gait cycle. This line of research builds upon the rich history of sensorimotor control research in which augmented sensory information (visual, haptic, or auditory) is used to probe, and even enhance, human motor control. This review paper focuses on gait control challenges in patients with vestibular dysfunction, provides a brief historical perspective on how various visual displays have been used to probe sensorimotor and gait control, and offers some recommendations for future research.

**Keywords:** Gait | virtual reality | visual stimuli | sensorimotor control

**Article:**

## 1. Introduction

The human body is made up of 206 bones, over 600 muscles, and millions of nerves and neurons. In order to walk, all these components must be coordinated in concert. This is the classic degrees-of-freedom problem outlined by Bernstein [10], which states that it is impossible for the central nervous system to sense and control each component individually. Rather, to reduce the control dimensionality, sensory information is integrated, allowing the brain to adhere to relatively few variables to sense movement consequences and to send neural commands to groups of muscle synergies [20]. The vestibular system's role in this coordinated effort is to monitor linear and angular acceleration of the head, which provides vital information needed to maintain upright stance and spatial orientation. Vestibular information, in conjunction with vision and proprioception, is integrated such that accurate feedforward and feedback control of motor behavior can be exhibited [21, 75].

There are a number of vestibular disorders of prevalence in the general population, including vestibular neuritis and Meniere's disease [1, 12, 84, 86]. Vestibular neuritis results from an infection on the VIII cranial nerve and causes a sudden interruption of neural information for the vestibular apparatus, and is one of the leading causes of vestibular hypofunction. Meniere's disease is likely caused by episodic disruption in inner ear fluid regulation. Individuals with Meniere's disease experience periods of altered hearing, severe dizziness and disequilibrium from an irritated sensory state, however overtime they will likely develop vestibular hypofunction and hearing loss. These disorders, along with others, pose a serious health problem because the resulting dizziness, imbalance, and/or hearing loss significantly affect quality of life and the ability to perform activities of daily living. Balance and gait are particularly adversely affected by vestibular dysfunction because the vestibular system plays a major role in providing sensory information required to stabilize head orientation during movement, ensure gaze stability, and to engage lower body musculature to maintain postural stability [34, 60]. Previous work has shown that 35.4% of adults 40 years and older have balance dysfunction related to vestibular system—a percentage that grows with increasing age [3]. Balance dysfunction has a profound effect on health quality, as it has been associated with increased fall risk [3], which can lead to physical, psychological, and financial consequences for the faller and their family [23, 44, 47, 72, 90, 91]. Collectively, health care costs in the United States related to falls across the lifespan are in the billions of dollars [13]. Due to individualized nature of each vestibular disorder, it has been suggested that an appropriate neuro-otological history and assessment, including clinical examination and vestibular function tests [19, 95], be used to tailor specific treatments to enhance balance and reduce fall risk [4].

To curb these health risks, rehabilitation programs aimed at enhancing gait control have been developed [34, 45, 51, 55, 57]. In this review paper we focus on gait training techniques that involve use of augmented visual feedback to improve motor function. Augmented feedback allows for the provision of information about relevant task variables and therefore may make it possible to return to locomotor activity quicker, which in turn may enhance the neural plasticity required to compensate for the impaired vestibular function. We first highlight specific alterations of gait behavior in patients with vestibular dysfunction. Next, we provide a brief overview of motor learning principles that could be used to design visual feedback displays and provide a brief review of how visual stimuli have been used to alter sensorimotor control strategies in healthy populations. The final two sections will review some current work in our lab that uses visual stimuli to enhance gait control and outline future directions for work in this area.

## 2. Gait control in populations with vestibular dysfunction

The influence of vestibular dysfunction on gait control is not stereotypical and depends on the exact location and type of damage to the vestibular system [34], so it is important to outline a range of possible gait alterations in this population. Vestibular function may potentially affect both "local" and "global" gait variables. Local level variables refer to motion at the joint or segment level, whereas global variables refer to observables that are a product of control of multiple joints/segments simultaneously (i.e., gait speed, stride time, stride length) [42, 70]. Given that the body is a series of connected links, a disruption in the information used in the control of these links is likely to be observed across multiple body segments and joints, as well as at the global level.

Starting with the local level and taking a superiorto-inferior perspective in describing gait behavior, trunk motion is typically greater in patients with vestibular dysfunction, especially when measured close to the onset of dysfunction [5, 97]. This creates a biomechanical consequence of horizontally moving the center of mass closer to the base of support during gait, which could decrease stability, depending on the direction of momentum and/or external perturbations. Given that lateral trunk motion is related to fall-risk [25], increased trunk movement could partially account for increased the fall-rate in patients with certain types of vestibular dysfunction [33]. However, it is important to note that overcompensation may also be present in some patients in the form of reduced head and/or trunk motion in an attempt to stabilize the vestibular system [5]. Therefore, there may be a “sweet spot” in observed movement variability such that too much or too little variability indicates altered motor function [79, 87, 89]. Further down the kinetic chain, altered motion of the lower-limb joints and segments has been observed in patients with vestibular dysfunction Chou et al. (2003) reported that older adults with complaints of ‘dizziness’ and ‘unsteadiness’ showed greater lateral excursions of the leading leg during obstacle crossing compared to healthy older adults, which in turn led to greater medial-lateral excursion of the trunk [15].

Global variables that are derived from multiple local variables are also often altered due to vestibular dysfunction. For example, decreased gait speed is frequently reported in subjects with vestibular disorders compared to control subjects [11, 24, 46]. The decrease in gait speed occurs due to decreased step frequency and step length [11]. Because similar gait alterations are also observed in healthy older adults, some authors have suggested that these gait adaptations are related to a general strategy aimed to increase safety of locomotion [11]. Another strategy frequently used by patients with vestibular disorders is to increase step and stance width [54]. Krebs et al. showed that step width is particularly likely to increase when there is a challenge to move faster than preferred step frequency [46]. Increased stance width provides a wider base of support and helps to maintain balance in the mechanically unstable medial-lateral plane [8]. Variability in gait timing is also typically increased in individuals with vestibular impairment [61], however that may also depend on the locomotor speed. Schniepp et al. reported that the coefficient of variation of stride time was increased to about 10% only at slow walking speeds, but was comparable to healthy controls at moderate and fast speeds [74].

To address these gait control challenges associated with vestibular dysfunction, a number of exercise-based rehabilitation programs have been developed [34, 35]. Vestibular rehabilitation programs typically include four exercise components focused on the following: (1) enhancing gaze stability (visual acuity when the head is moving), (2) habituating (or desensitizing) symptoms, (3) improving static and dynamic balance and gait, and (4) improve endurance [28]. While many of these practices have been shown to enhance gait function [14, 93], combining information from studies examining the use of visual feedback from the sensorimotor control literature with advancements in technology might provide ways to enhance gait control more precisely. The next section highlights relevant sensorimotor learning principles that could be useful in developing novel rehabilitation techniques for patients with vestibular dysfunction.

## 3. Uses of visual information to alter sensorimotor control

There are two types of motor learning currently discussed in the literature: motor adaptation and skill learning [81]. Motor adaptation refers to the re-calibration visuo-motor mapping of an already well-learned movement pattern (such as locomotion and reaching) after a visual or force-field perturbation. Adaptation is highly dependent on receiving error information about the performance. In this type of learning the detected error is used to update the next movement to more accurately achieve the goal movement on the next attempt. Motor skill learning, on the other hand, involves acquisition of a novel movement pattern *de novo*. It could be argued that recovery from inner ear pathology involves utilization of the remaining normal function to re-equilibrate the dysfunctional behavior, making motor adaptations more important in this context. Adapting the remaining motor function to new tasks can be developed by using augmented feedback, which has a long history in the motor control literature and refers to using information received from an external source (i.e. outside the body) [73]. Generally speaking, augmented feedback provided in the context of motor adaptation or skill learning allows more effective error correction because it provides information about movement error over and beyond what is provided by the inherent sensory feedback systems.

Determining exactly how feedback is delivered is an important consideration. It can be presented either during or after the movement. Presentation during movement can take the form of showing an online movement trajectory or signaling change in display color that is linked to the aspect of movement being trained. Post-movement feedback—also termed knowledge of results—is also frequently used where subjects are provided with a score or some summary metric about their previous movement with respect to task goal. Such feedback has both informational and motivational value to the learners.

One important consideration for designing feedback displays is that many movements we learn are redundant – meaning that they can be performed in a variety of ways. For example, one can grab a cup of tea using many different hand configurations and approach trajectories. Such redundancy is good because it provides flexibility in performance and allows room for inherent variability that is present in the motor system. One principle of motor skill learning that has been proposed for redundant movements is that humans tend to converge on task solutions that minimize the adverse effects of intrinsic noise and variability on the quality of performance [81].

Redundant movements pose a challenge to decide which aspects of behavior one should emphasize to provide feedback and this may depend on the learning goal. When the optimal, desired form of movement is not known, it may be better to use unsupervised learning such that the performer is allowed explore and discover his/her own way of doing the task without any explicit feedback about how to achieve the goal in particular. Accordingly, one can create visual displays that that encourage exploration—this can be achieved by using very sparse feedback only about the result of the movement outcome (e.g., hit or miss).

In cases where the exact form of the desired behavior is known (e.g., to make gait more symmetrical), one can help the performer discover this solution by implicitly guiding them by using targeted modifications of visual feedback. For example, Kim & Krebs reported using visual feedback of step length symmetry that was distorted so that subjects perceived their step length as being asymmetric during treadmill training [43]. Throughout training, young healthy adults, without consciously realizing the distortion of the feedback, gradually shifted their weight distribution. Such strategy could be used to train patients with weight-bearing asymmetries. Another example of this strategy is an experiment on visually guided ball bounding in a virtual ball bouncing task [36]. In this task, hitting the ball in the particular phase of the racket cycle leads to passively stable dynamics of the task (i.e., where the task can be performed without the perceptually-demanding racket corrections to the racket position). Huber and Sternad delayed visual feedback of the racket which implicitly guided the performers to hit the ball in the passively stable regime, which led to a better performance on the task [36].

Another consideration in designing visual feedback displays is that one can take advantage of typical motor system preferences to optimize learning. Kelso and colleagues discovered the boundaries of stable and unstable behavior, described as the Haken-Kelso-Bunz (HKB) model, in basic motor coordination activities [38]. Recently, the HKB model has been applied to lower-limb coordination to better understand gait control [69]. An important contribution of this work is the discovery of patterns of behavior that are naturally stable. For example, moving the index fingers in a 1:1 timing ratio either in-phase (i.e., moving in the same direction) or in anti-phase (i.e., moving in the opposite direction) represents a stable behavior. However, asking the participant to alter their timing ratio to 4:3, for example, is nearly impossible for most people. That is, unless the sensorimotor system is ‘tricked’. In order to create stable coordination patterns, feedback from the sensory systems is used to control the motor system [76]. When sensory information is modulated in a particular manner, then previously unstable patterns of behavior emerge as stable. An example of this is the clever experiment by Meschner and colleagues where they modified the visual feedback of participants performing a variety of coordination tasks [56]. Participants were asked to create a 1:1 timing ratio of two rotating cranks. However, the control of the cranks were hidden under a table, so the participants were not afforded visual feedback of their motor behavior. Using a gear system, the researchers required a 4:3 timing ratio with the cranks under the table in order to create a visual 1:1 ratio. Even though the 4:3 ratio is a very unstable behavior, participants were able to consistently create this behavior when their visual feedback indicated it was a 1:1 ratio. This is an excellent example of how sensory information can be modulated to produce the desired motor behavior.

The research on motor learning and its application to rehabilitation has been recently further extended through the use of virtual reality. Keshner and colleagues were early leaders in this area by using immersive virtual reality in which participants stood or walked inside an environment that had images projected on the walls and the floor [39, 40]. Using stereo glasses, the immersive environment allowed the participants to perceive that they were inside the virtual environment. This methodology provided a pathway for the researchers to alter visual information in a manner that allowed them to titrate out the influence of the vestibular system on gait and balance [22, 29, 41, 94].

Virtual reality can be used for rehabilitation in a prescriptive manner using either a pre-packaged or custom approach. An example of the pre-packaged approach is to use off-the-shelf hardware and software, such as the Nintendo Wii or Microsoft Kinect, and examine how sensorimotor control changes as a function of playing the game. The so called Exergaming approach has been used as a modality to enhance gait and balance control in older adults [2, 48, 71], and this type of intervention has recently been extended to patients with vestibular dysfunction [92]. An alternative approach is to develop a custom virtual reality “game” that targets a specific aspects of sensorimotor control. For example, if gait control is affected due to excessive trunk rotation, a virtual realty game could be created that trains the patient to reduce trunk motion. That is, visual information can be manipulated within the virtual environment in an individualized, specific manner to enhance patient-centered rehabilitation. However, one needs to remember that the design of these “games” should remain rooted in the theory of motor control [80].

In the context of rehabilitation of patients with vestibular dysfunction, it is important to consider that their visual system may also be impaired due to poor visual-ocular reflex or vestibulocollic reflex. There is much work that has explored the use of augmented feedback in the auditory and haptic domains [76] that could also be used to enhance motor control. However, the rest of this review paper will focus on the use of visual information to modulate motor behavior, as this is the modality that has been the most studied recently with respect to sensorimotor control [76]. In addition, training of the visual gaze acuity is also one of the goals of vestibular rehabilitation therapy, so practicing to effectively use additional visual information may improve sensory substitution for vestibular function and help retrain any residual vestibular function.

## 4. Using visual stimuli to enhance gait control

Hundreds of risk factors have been associated with falls, ranging from sensory and neuromuscular factors to medical factors to medication and environmental factors [50]. However, there has been no appreciable decline in fall-rate across society, so there is still much to learn about the optimal way to enhance gait control and implement such programs at a small and large scale. While fall-risk is inherently multifactorial, there are a number of candidate gait variables that have been closely linked to fall-risk. These include both temporal and spatial aspects of the gait cycle at both the local and global level, and researchers have begun to explore the use of visual feedback displays and protocols to specifically modulate these characteristics of gait in order to modify gait control [30].

For example, motion of the trunk is known to relate to fall-risk [26, 27]. Two-thirds of the body’s mass is above the waist [98], so any excess motion could reduce stability from a mechanical perspective. Individuals with vestibular dysfunction have been shown to have increased trunk motion profiles [5, 97], so using visual feedback to reduce trunk motion could be a useful modality to learn a new motor pattern. Anson and colleagues explored this postulate with younger and older adults and found that trunk translation variability was reduced in while walking on the treadmill, but without any appreciable changes in the variability of trunk orientation [6]. The ability to exert translational control in the medial-lateral plane would be useful for vestibular patients because it would improve directional consistency of locomotion, which has been reported to be impaired in this population [11, 24].

Step width is a global variable that is also biomechanically linked to fall-risk [58]. A consistently narrow step width reduces the base of support in which the center of mass can move. A person is less stable as the center of mass gets closer to their base of support. Thus, adopting a wider base of support represents a more stable walking pattern. While we could not locate any studies that used visual feedback explicitly about step width, one study provided visual feedback on the kinematics of hip internal rotation angle [88], which led to a modification of step width in healthy young adults in addition to the desired effect of reducing knee adduction. Another study used auditory feedback to explicitly increase stance width in individuals with hemiparesis such that subjects received an auditory signal (a beep) every time the distance between the feet was small [7]. After 10 days of conventional gait therapy coupled with the auditory feedback, these patients increased their step width to a greater extent than the group without the auditory feedback.

Lastly, stride timing variability is related to fall-risk [31, 58]. Stride timing is measured as the duration from heel contract on one limb to heel contact on the same limb during walking. It is a global variable that reflects motion of the entire body throughout the entire kinetic chain. Further, stride time variability has been shown to exhibit fractal patterns in young healthy adults [32]. Fractal patterns describe a structure that repeats across time or spatial scales, a characteristic that was conceptually and mathematically described by Mandelbrot [53]. Visually, fractal patterns result in statistically persistent fluctuations such that there is a pattern of observations falling consistently above the mean followed by segments below the mean. This is in contrast to random patterns which are characterized by falling above and below the mean in a random fashion. Fractal patterns in physiology have been suggested to reflect a healthy and adaptive system, evidenced by a weakening of the self-similarity of patterns in aged or diseased systems [9, 52, 96]. This led to the "loss of complexity" theory, suggesting that lower functional ability is associated with a weakening in repeating patterns of behavior in whichever system is being observed [49]. For example, weaker fractal patterns in the beat-to-beat timing of cardiac behavior have been associated with cardiac dysfunction. This framework has been extended to encompass any deviation in dynamic patterns from the normal state (i.e., weakening or strengthening) to represent a system's decrease in functional ability [79, 87]. Furthermore, this framework has been extensively explored relative to gait behavior over the past three decades and it has been suggested as an objective way to quantify the adaptive capacity of the gait system [31, 65]. This is attractive, as clinical assessment often relies on subjective assessment of gait behavior. Thus, the dynamics of gait behavior might be used to not only index a patient's current functional status, but they also might be manipulated in a specific manner in order to restore functional mobility using fractal gait re-training protocols.

## 5. Fractal training visual displays

The seemingly simple task of finger tapping at a particular pace has been used to probe the characteristics of human sensorimotor control since the work of Stevens, who was the first to document the presence of patterns of fluctuations in the inter-tap intervals during tapping [82]. In more recent studies, researchers typically ask participants to synchronize their movement timing (commonly finger tapping or circle drawing) to a metronome for a short duration and then monitor their timing performance once the metronome is removed [37, 64, 68, 83, 100]. Continuous movement synchronization with the metronome has also been extensively studied. These paradigms have led to a stronger understanding of how sensory modalities and the type of feedback influences motor timing variability [63], as well as theories of how different neural structures participate in motor timing [77]. Finger tapping and leg movements during gait both require the nervous system to generate precise timing and, therefore, findings from the literature on finger tapping [62, 63] could be useful with respect to designing new gait training protocols.

The first study to explore the possibility of altering fractal timing focused on introducing fractal variation during tapping tasks. Stephen and colleagues used a visual metronome (i.e., a flashing square on a computer screen) as a visual stimulus to which participants were asked to synchronize the timing of their finger tapping on a keyboard [78]. Rather than using an equal amount of time between each appearance of the pacing square, the experimenters varied the time between the visual flash such that it exhibited a fractal time structure. That is, some intervals were shorter and some were longer, exhibiting either persistent patterns (where longer intervals tend to follow longer ones, where "longer" is defined with respect to the mean) or anti-persistent patterns (where longer intervals tend to follow shorter intervals) within the variance. It was found that the fractal structure in the finger tapping could be manipulated by altering the fractal structure of the visual metronome time series. This was an important discovery, as it was the first to show that motor behavior fractal patterns could be altered in a specific manner.

To determine if this finding extends to gait control, we conducted a proof-of-concept experiment to determine whether fractal patterns in gait could be strengthened or weakened using a similar visual stimulus as Stephen and colleagues. Participants were asked to synchronize their stride time to a visual metronome presented on a projection screen in front of a treadmill. The timing between the visual metronome "beats" was prescribed as either persistent or anti-persistent. We discovered the fractal gait patterns are indeed altered in specified direction, suggesting that the fractal training framework can be extended to study gait control [66]. In a follow-up study, it was shown that the new fractal gait patterns are retained directly after the training, showing that the change in fractal gait patterns was not just a stimulus response behavior [67]. Rather, the findings suggested that a reorganization in neuromotor behavior occurred, allowing the new fractal patterns to be exhibited even after the stimulus was removed. These findings could be the beginning of a new way to use visual stimuli to enhance gait control. However, there are a number of empirical questions that need to be more fully examined, such as the use of a presentation of a discrete versus continuous stimulus (which was partially explored in [67]), the role of feedback in the learning of fractal gait patterns, and whether the fractal pattern should be artificially constructed or derived from a biological system [85].

However, the utility of visual feedback to enhance gait control is not confined to manipulating fractal patterns in stride time. For example, if trunk motion was the primary variable to manipulate, then an avatar could be used to give real-time feedback about the patient's trunk motion. Some Exergames use this concept by integrating motion capture with their software within their pre-packaged game. However, the field of gait rehabilitation can benefit from an open-source approach that allows researchers using a common platform to modify their variables of interest (e.g., step width, step length, stride timing, trunk motion, etc.) in a specified manner in order to teach the patient the desired gait behavior. For example, Microsoft offers a Software Development Kit (SDK) for their Kinect system, which has been used as both an assessment and rehabilitation tool to enhance gait and balance [16, 17, 59, 99]. This approach allows for a structured, yet diversified approach to examining how visual stimuli can be manipulated to enhance gait control across a variety of clinical populations.

## 6. Using fractal gait training in patient populations with vestibular disorders

Each vestibular disorder has a unique pathophysiology, many of which can lead to gait and balance dysfunction [60], ultimately leading to increased fall-risk [3]. Due to the uniqueness not only between vestibular disorders, but also between patients with the same disorder, there is a strong need for proper neuro-otological history taking and assessment in order to develop a tailored rehabilitation program to enhance gait/balance function [4]. Since weak fractal gait patterns have been related to increased fall-risk [31], it is logical to think that strengthening fractal gait patterns would lead to a decreased fall-risk. However, this logic is likely context dependent—meaning that a patient-centered approach might be complimented by including an individualized fractal gait training program. If a patient is found to have altered stride timing, then asking them to synchronize their steps to an appropriate fractal visual display may enhance their walking function (and decrease fall-risk) by challenging their neuromotor control through micro-perturbations provided by the requirement of slightly altering their stride-to-stride behavior, allowing the locomotor system to adapt to the altered vestibular information. The meaningfulness of this type of training will likely be different for patients with acute and chronic vestibular disorders. To date, there is no literature merging fractal gait training with patient populations who have vestibular disorders, so the efficacy of this type of training and potential mechanistic relationships if a positive change in gait/balance behavior were observed have yet to be explored.

## 7. Future directions

While there appears to be promise in the use of visual stimuli to enhance gait control, there are a number of empirical questions need to be more fully explored to describe the clinical utility of such an approach. For example, does changing a particular gait variable alter fall-risk post-training? To address this question, a systematic approach is needed to understand which candidate variables are related to fall-risk, determine which of the candidate variables are modifiable, and then determine how to modify them without any unintended consequences. This is a non-trivial issue, as the body consists of countless interacting parts, so altering one aspect of gait control likely causes some other part of gait control to change (which may be adaptive or maladaptive in the long run). Further, the ability to monitor gait has changed rapidly in the past few years and could be further utilized in future studies. The rapid advancement of smartphone sensors and other portable devices allows for an exploration of gait behavior in the real world in a manner that was not possible before. This could allow for the development of remote data sets and potentially a 'big data' approach to help better understand how factors associated with fall-risk interact, which may help develop a personalized approach to gait rehabilitation. Finally, relative to vestibular dysfunction, it is almost certain that a one-size-fits-all approach to gait rehabilitation will not work. Determining which visual stimuli are useful to enhance gait control in populations with particular vestibular etiologies would help deliver individualized gait rehabilitation.

## Acknowledgments

The authors would like to thank Dr. Anne Galgon for her clinical insights in this paper.

## References


[1] I. Adamec, M.K. Skori´c, J. Handˇzi´c and M. Habek, Incidence, seasonality and comorbidity in vestibular neuritis, *Neurological Sciences* **36** (2015), 91–95.

[2] M. Agmon, C.K. Perry, E. Phelan, G. Demiris and H.Q. Nguyen, A pilot study of Wii Fit exergames to improve balance in older adults, *Journal of Geriatric Physical Therapy* **34** (2011), 161–167.

[3] Y. Agrawal, J.P. Carey, C.C. Della Santina, M.C. Schubert and L.B. Minor, Disorders of balance and vestibular function in US adults: Data from the National Health and Nutrition Examination Survey, 2001-2004, *Archives of Internal Medicine* **169** (2009), 938–944.

[4] Y. Agrawal, B.K. Ward and L.B. Minor, Vestibular dysfunction: Prevalence, impact and need for targeted treatment, *Journal of Vestibular Research: Equilibrium* & *Orientation* **23** (2013), 113.

[5] J.H. Allum and A.L. Adkin, Improvements in trunk sway observed for stance and gait tasks during recovery from an acute unilateral peripheral vestibular deficit, *Audiology and Neurotology* **8** (2003), 286–302.

[6] E. Anson, R. Rosenberg, P. Agada, T. Kiemel and J. Jeka, Does visual feedback during walking result in similar improvements in trunk control for young and older healthy adults? *Journal of Neuroengineering and Rehabilitation* **10** (2013), 1.

[7] A.S. Aruin, T.A. Hanke and A. Sharma, Base of support feedback in gait rehabilitation, *International Journal of Rehabilitation Research* **26** (2003), 309–312.

[8] C.E. Bauby and A.D.Kuo, Active control of lateral balance in human walking, *Journal of Biomechanics* **33** (2000), 1433–1440.

[9] J.B´elair,L. Glass, U. an der Heiden and J. Milton, Dynamical disease: Identification, temporal aspects and treatment strategies of human illness, *Chaos: An Interdisciplinary Journal of Nonlinear Science* **5** (1995), 1–7.

[10] N. Bernstein, The coordination and regulation of movements, Pergamon, London, 1967.

[11] L. Borel, F. Harlay, C. Lopez, J. Magnan, A. Chays and M. Lacour, Walking performance of vestibular-defective patients before and after unilateral vestibular neurotomy, *Behavioural Brain Research* **150** (2004), 191–200.

[12] J.R. Brodsky, B.A. Cusick and G. Zhou,Vestibular neuritis in children and adolescents: Clinical features and recovery, *International Journal of Pediatric Otorhinolaryngology* **83** (2016), 104–108.

[13] N.V. Carroll, P.W. Slattum and F.M. Cox, The cost of falls among the community-dwelling elderly, *Journal of Managed Care Pharmacy* **11** (2005), 307–316.

[14] W.-C. Chang, Y.-R. Yang, L.-C. Hsu, C.-M. Chern and R.-Y. Wang, Balance improvement in patients with benign paroxysmal positional vertigo, *Clinical Rehabilitation* **22** (2008), 338–347.

[15] L.-S. Chou, K.R. Kaufman, M.E. Hahn and R.H. Brey, Medio-lateral motion of the center of mass during obstacle crossing distinguishes elderly individuals with imbalance, *Gait* & *Posture* **18** (2003), 125–133.

[16] R.A. Clark, K.J. Bower, B.F. Mentiplay, K. Paterson and Y.-H. Pua, Concurrent validity of the Microsoft Kinect for assessment of spatiotemporal gait variables, *Journal of Biomechanics* **46** (2013), 2722–2725.

[17] R.A. Clark, Y.-H. Pua, A.L. Bryant and M.A. Hunt, Validity of the Microsoft Kinect for providing lateral trunk lean feedback during gait retraining, *Gait* & *Posture* **38** (2013), 1064–1066.

[18] H.S. Cohen and K.T. Kimball, Increased independence and decreased vertigo after vestibular rehabilitation, *Otolaryngology–Head and Neck surgery* **128** (2003), 60–70.

[19] I.S. Curthoys, The interpretation of clinical tests of peripheral vestibular function, *The Laryngoscope* **122** (2012), 1342–1352.

[20] A. d'Avella, P. Saltiel and E. Bizzi, Combinations of muscle synergies in the construction of a natural motor behavior, *Nature Neuroscience* **6** (2003), 300–308.

[21] B.L. Day and M. Guerraz, Feedforward versus feedback modulation of human vestibular-evoked balance responses by visual self-motion information, *The Journal of Physiology* **582** (2007), 153–161.

[22] K. Dokka, R.V. Kenyon, E. Keshner and K.P. Kording, Self versus environment motion in postural control, *PLoS Computational Biology* **6** (2010), e1000680.

[23] J. Fast, N.C. Keating and J. Eales, Economic impact of health, income security and labour policies on informal caregivers of frail seniors, Status of Women Canada Ottawa, ON, 2001.

[24] S. Glasauer, M.-A. Amorim, E.Vitte and A. Berthoz, Goal-directed linear locomotion in normal and labyrinthine-defective subjects, *Experimental Brain Research* **98** (1994), 323–335.

[25] M. Grabiner, S. Donovan, M. Bareither, J. Marone, K. Hamstra-Wright, S. Gatts and K. Troy, Trunk kinematics and fall risk of older adults: Translating biomechanical results to the clinic, *J Electromyogr Kinesiol* **18** (2008), 197–204.

[26] M. Grabiner, J. Feuerbach and D. Jahnigen, Successful recovery from a trip: Control of the trunk during the initial phase following perturbation, *Journal of Biomechanics* **29** (1996), 735–744.

[27] M. Grabiner, T.Koh, T. Lundin and D. Jahnigen, Kinematics of recovery from a stumble, *Journal of Gerontology* **48** (1993), M97–M102.

[28] C.D. Hall, S.J. Herdman, S.L. Whitney, S.P. Cass, R.A. Clendaniel, T.D. Fife, J.M. Furman, T.S. Getchius, J.A. Goebel and N.T. Shepard, Vestibular rehabilitation for peripheral vestibular hypofunction: An evidence-based clinical practice guideline, *Journal of Neurologic Physical Therapy* **40** (2016), 124–155.

[29] F.J. Haran and E. Keshner, Sensory reweighting as a method of balance training for labyrinthine loss, *Journal of Neurologic Physical Therapy* **32** (2008), 186.

[30] C.J. Hasson, J. Manczurowsky and S.-C.Yen,A reinforcement learning approach to gait training improves retention, *Frontiers in Human Neuroscience* **9** (2015), 459.

[31] J.M. Hausdorff, Gait dynamics, fractals and falls: Finding meaning in the stride-to-stride fluctuations of human walking, *Human Movement Science* **26** (2007), 555–589.

[32] J.M. Hausdorff, C.K. Peng, Z. Ladin, J.Y. Wei and A.L. Goldberger, Is walking a random walk? Evidence for long-range correlations in stride interval of human gait, *Journal of Applied Physiology* **78** (1995), 349–358.

[33] S.J. Herdman, P. Blatt, M.C. Schubert and R.J. Tusa, Falls in patients with vestibular deficits, *Otology* & *Neurotology* **21** (2000), 847–851.

[34] S.J. Herdman and R. Clendaniel, Vestibular Rehabilitation, FA Davis, Philadelphia, PA, 2014.

[35] S. Hillier and M. McDonnell, Vestibular rehabilitation for unilateral peripheral vestibular dysfunction,Wiley Online Library, 2011.

[36] M.E. Huber and D. Sternad, Implicit guidance to stable performance in a rhythmic perceptual-motor skill, *Experimental Brain Research* **233** (2015), 1783–1799.

[37] R.B. Ivry and R.E. Hazeltine, Perception and production of temporal intervals across a range of durations: Evidence for a common timing mechanism, *Journal of Experimental Psychology: Human Perception and Performance* **21** (1995), 3–18.

[38] J.A.S. Kelso, Dynamic patterns: *The self-organization of brain and behavior*, Cambridge, MA, The MIT Press, (1995).

[39] E. Keshner, Virtual reality and physical rehabilitation: A new toy or a new research and rehabilitation tool? *Journal of Neuroengineering and Rehabilitation* **1** (2004), 8.

[40] E. Keshner and R.V. Kenyon, The influence of an immersive virtual environment on the segmental organization of postural stabilizing responses, *Journal of Vestibular Research* **10** (2000), 207–219.

[41] E. Keshner, R.V. Kenyon and J. Langston, Postural responses exhibit multisensory dependencies with discordant visual and support surface motion, *Journal of Vestibular Research* **14** (2004), 307–319.

[42] A.W. Kiefer, C.K. Rhea and W.H. Warren, VR-based assessment and rehabilitation of functional mobility, in: *Human Walking in Virtual Environments: Perception, Technology, and Applications*, J. Campos ed., Springer Verlag, Dusseldorf, Germany, 2013.

[43] S.-J. Kim and H.I. Krebs, Effects of implicit visual feedback distortion on human gait, *Experimental Brain Research* **218** (2012), 495–502.

[44] M.R. Kosorok, G.S. Omenn, P. Diehr, T.D. Koepsell and D.L. Patrick, Restricted activity days among older adults, *American Journal of Public Health* **82** (1992), 1263–1267.

[45] D. Krebs, K. Gill-Body, P. Riley and S. Parker, Double-blind, placebo-controlled trial of rehabilitation for bilateral vestibular hypofunction: Preliminary report, *Otolaryngology–Head and Neck Surgery* **109** (1993), 735–741.

[46] D.E. Krebs, D. Goldvasser, J.D. Lockert, L.G. Portney and K.M. Gill-Body, Is base of support greater in unsteady gait? *Physical Therapy* **82** (2002), 138–147.

[47] M. Kuzuya, Y. Masuda, Y. Hirakawa,M. Iwata, H. Enoki, J. Hasegawa, S. Izawa and A. Iguchi, Falls of the elderly are associated with burden of caregivers in the community, *International Journal of Geriatric Psychiatry* **21** (2006), 740–745.

[48] C. Lamoth, S.R. Caljouw and K. Postema, Active video gaming to improve balance in the elderly, *Stud Health Technol Inform* **167** (2011), 159–164.

[49] L.A. Lipsitz and A.L. Goldberger, Loss of 'complexity' and aging: Potential applications of fractals and chaos theory to senescence, *JAMA: The Journal of the American Medicine Association* **267** (1992), 1806–1809.

[50] S.R. Lord, C. Sherrington, H.B. Menz and J.C. Close, Falls in older people: Risk factors and strategies for prevention, Cambridge University Press, New York, NY, 2007.

[51] J.D. Macias, S. Massingale and R.D. Gerkin, Efficacy of vestibular rehabilitation therapy in reducing falls, *Otolaryngology-Head and Neck Surgery* **133** (2005), 323–325.

[52] M.C. Mackey and J.G. Milton, Dynamical diseases, *Annals of the New York Academy of Sciences* **504** (1987), 16–32.

[53] B.B. Mandelbrot, The Fractal Geometry of Nature, Freeman, New York, 1982.

[54] G.F. Marchetti, S.L. Whitney, P.J. Blatt, L.O. Morris and J.M. Vance, Temporal and spatial characteristics of gait during performance of the Dynamic Gait Index in people with and people without balance or vestibular disorders, *Physical Therapy* **88** (2008), 640–651.

[55] C.A. McGibbon, D.E. Krebs, S.W. Parker, D.M. Scarborough, P.M. Wayne and S.L. Wolf, Tai Chi and vestibular rehabilitation improve vestibulopathic gait via different neuromuscular mechanisms: Preliminary report, *BMC Neurology* **5** (2005), 3.

[56] F. Mechsner,D.Kerzel, G. Knoblich andW. Prinz, Perceptual basis of bimanual coordination, *Nature* **414** (2001), 69–73.

[57] D. Meldrum, S. Herdman, R. Moloney, D. Murray, D. Duffy, K. Malone, H. French, S. Hone, R. Conroy and R. McConn-Walsh, Effectiveness of conventional versus virtual reality based vestibular rehabilitation in the treatment of dizziness, gait and balance impairment in adults with unilateral peripheral vestibular loss: A randomized controlled trial, *BMC Ear, Nose and Throat Disorders* **12** (2012), 1.

[58] N. Mortaza, N. Abu Osman and M. Mehdikhani, Are the spatio-temporal parameters of gait capable of distinguishing a faller from a non-faller elderly, *Eur J Phys Rehabil Med* **50** (2014), 677–691.

[59] H. Mousavi Hondori and M. Khademi, A review on technical and clinical impact of microsoft kinect on physical therapy and rehabilitation, *Journal of Medical Engineering* **2014** (2014).

[60] L. Murdin and A.G. Schilder, Epidemiology of balance symptoms and disorders in the community: A systematic review, *Otology* & *Neurotology* **36** (2015), 387–392.

[61] S. Perring and T. Summers, Laboratory-free measurement of gait rhythmicity in the assessment of the degree of impairment and the effectiveness of rehabilitation in patients with vertigo resulting from vestibular hypofunction, *Physiological Measurement* **28** (2007), 697–705.

[62] B.H. Repp, Sensorimotor synchronization: A review of the tapping literature, *Psychonomic Bulletin* & *Review* **12** (2005), 969–992.

[63] B.H. Repp, Sensorimotor synchronization and perception of timing: Effects of music training and task experience, *Human Movement Science* **29** (2010), 200–213.

[64] B.H. Repp and S.R. Steinman, Simulataneous event-based and emergent timing: Synchronization, continuation, and phase correction, *Journal of Motor Behavior* **42** (2010), 111–126.

[65] C.K. Rhea and A.W. Kiefer, Patterned variability in gait behavior: How can it be measured and what does it mean?, in: *Gait Biometrics: Basic Patterns*, *Role of Neurological Disorders and*

*Effects of Physical Activity*, L. Li and M. Holmes eds., Nova Science Publishers, Hauppauge, NY, 2014.

[66] C.K. Rhea, A.W. Kiefer, S.E. D'Andrea, W.H. Warren and R.K. Aaron, Entrainment to a real time fractal visual stimulus modulates fractal gait dynamics, *Human Movement Science* **36** (2014), 20–34.

[67] C.K. Rhea, A.W.W. Kiefer, M.W. Wittstein, K.B. Leonard, R.P. MacPherson, W.G. Wright and F.J. Haran, Fractal gait patterns are retained after entrainment to a fractal stimulus, *PLoS One* **9** (2014), e106755.

[68] S.D. Robertson, H.N. Zelaznik, D.A. Lantero, K.G. Bojczyk, R.M. Spencer, J.G. Doffin and T. Schneidt, Correlations for timing consistency among tapping and drawing tasks: Evidence against a single timing process, *Journal of Experimental Psychology: Human Perception and Performance* **25** (1999), 1316–1330.

[69] D.M. Russell, J.L. Haworth and C. Martinez-Garza, Coordination dynamics of (a) symmetrically loaded gait, *Experimental Brain Research* (2015), 1–15.

[70] H. Sadeghi, Local or global asymmetry in gait of people without impairments, *Gait*& *Posture* **17** (2003), 197–204.

[71] K. Sato, K. Kuroki, S. Saiki and R. Nagatomi, Improving walking, muscle strength, and balance in the elderly with an exergame using Kinect: A randomized controlled trial, *Games for Health Journal* **4** (2015), 161–167.

[72] R.W. Sattin, D.A.L. Huber, C.A. Devito, J.G. Rodriguez, A. Ros, S. Bacchelli, J.A. Stevens and R.J. Waxweiler, The incidence of fall injury events among the elderly in a defined population, *American Journal of Epidemiology* **131** (1990), 1028–1037.

[73] R. Schmidt and T. Lee, Sensory contributions to motor control, *Motor Control and Learning: A Behavioural Emphasis* **4** (2005), 125–162.

[74] R. Schniepp, M. Wuehr, M. Neuhaeusser, M. Kamenova, K. Dimitriadis, T. Klopstock, M. Strupp, T. Brandt and K. Jahn, Locomotion speed determines gait variability in cerebellar ataxia and vestibular failure, *Movement Disorders* **27** (2012), 125–131.

[75] R. Seidler, D. Noll and G. Thiers, Feedforward and feedback processes in motor control, *Neuroimage* **22** (2004), 1775–1783.

[76] R. Sigrist, G. Rauter, R. Riener and P. Wolf, Augmented visual, auditory, haptic, and multimodal feedback in motor learning: A review, *Psychonomic Bulletin* & *Review* **20** (2013), 21–53.

[77] R.M.C. Spencer, H.N. Zelaznik, J. Diedrichsen and R.B. Ivry, Disrupted timing of discontinuous but not continuous movements by cerebellar lesions, *Science* **300** (2003), 1437–1439.

[78] D.G. Stephen, N. Stepp, J.A. Dixon and M.T. Turvey, Strong anticipation: Sensitivity to long-range correlations in synchronization behavior, *Physica A* **387** (2008), 5271–5278.

79] N. Stergiou, R.T. Harbourne and J.T. Cavanaugh, Optimal movement variability: A new theoretical perspective for neurologic physical therapy, *Journal of Neurologic Physical Therapy* **30** (2006), 120–129.

[80] D. Sternad, From theoretical analysis to clinical assessment and intervention: Three interactive motor skills in a virtual environment, in: *2015 International Conference on Virtual Rehabilitation Proceedings (ICVR)* IEEE, 2015, pp. 265–272.

[81] D. Sternad, M.E. Huber and N.A. Kuznetsov, Acquisition of novel and complex motor skills: Stable solutions where intrinsic noise matters less, *Advances in Experimental Medicine and Biology* **826** (2014), 101–124.

[82] L. Stevens, On the time sense, *Mind* **11** (1886), 393–404.

[83] B.E. Studenka and H.N. Zelaznik, The influence of dominant versus non-dominant hand on event and emergent motor timing, *Human Movement Science* **27** (2008), 29–52.

[84] T.L. Thompson and R. Amedee, Vertigo: A review of common peripheral and central vestibular disorders, *The Ochsner Journal* **9** (2009), 20–26.

[85] N.F. Troje, C. Westhoff and M. Lavrov, Person identification from biological motion: Effects of structural and kinematic cues, *Perception* & *Psychophysics* **67** (2005), 667–675.

[86] J.S. Tyrrell, D.J. Whinney, O.C. Ukoumunne, L.E. Fleming and N.J. Osborne, Prevalence, associated factors, and comorbid conditions for Meniere's disease, *Ear and Hearing* **35** (2014), e162–e169.

[87] D.E. Vaillancourt and K. Newell, Changing complexity in human behavior and physiology through aging and disease, *Neurobiology of Aging* **23** (2002), 1–11.

[88] J.C. van den Noort, F. Steenbrink, S. Roeles and J. Harlaar, Real-time visual feedback for gait retraining: Toward application in knee osteoarthritis, *Medical* & *Biological Engineering* & *Computing* **53** (2015), 275–286.

[89] G. Van Orden, The fractal picture of health and wellbeing, in: *Psychological Science Agenda*, 2007.

[90] B.J. Vellas, F. Cayla, H. Bocquet, F. De Pemille and J. Albarede, Prospective study of restriction of acitivty in old people after falls, *Age and Ageing* **16** (1987), 189–193.

[91] B.J. Vellas, S.J. Wayne, L.J. Romero, R.N. Baumgartner and P.J. Garry, Fear of falling and restriction of mobility in elderly fallers, *Age and Ageing* **26** (1997), 189–193.

[92] D.H. Verdecchia, M. Mendoza, F. Sanguineti and A.C. Binetti, Outcomes after vestibular rehabilitation and Wii® therapy in patients with chronic unilateral vestibular hypofunction, *Acta Otorrinolaringologica* **65** (2014), 339–345.

[93] L. Vereeck, F.L. Wuyts, S. Truijen, C. De Valck and P.H. Van de Heyning, The effect of early customized vestibular rehabilitation on balance after acoustic neuroma resection, *Clinical Rehabilitation* **22** (2008), 698–713.

[94] Y.Wang, R.V.Kenyon and E.Keshner, Identifying the control of physically and perceptually evoked sway responses with coincident visual scene velocities and tilt of the base of support, *Experimental Brain Research* **201** (2010), 663–672.

[95] M.S. Welgampola, G. Akdal and G.M. Halmagyi, Neuro-otology-some recent clinical advances, *Journal of Neurology* (2016), 1–16.

[96] B.J. West and A.L. Goldberger, Physiology in fractal dimensions, *American Scientist* **75** (1987), 354–365.

[97] K. Wilhelmsen, S.H. Glad Nordahl and R. Moe-Nilssen, Attenuation of trunk acceleration during walking in patients with unilateral vestibular deficiencies, *Journal of Vestibular Research* **20** (2010), 439–446.

[98] D.A. Winter, Human balance and posture control during standing and walking, *Gait* & *Posture* **3** (1995), 193–214.

[99] L. Yeung, K.C. Cheng, C. Fong,W.C. Lee and K.-Y. Tong, Evaluation of the Microsoft Kinect as a clinical assessment tool of body sway, *Gait* & *Posture* **40** (2014), 532–538.

[100] H.N. Zelaznik, R.M.C. Spencer and R.B. Ivry, Dissociation of explicit and implcit timing in repetitive tapping and drawing movements, *Journal of Experimental Psychology: Human Perception and Performance* **28** (2002), 575–588.