Virtual reality-based assessment and rehabilitation of functional mobility

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Abstract:

The advent of virtual reality (VR) as a tool for real-world training dates back to the mid-twentieth century and the early years of driving and flight simulators. These simulation environments, while far below the quality of today's visual displays, proved to be advantageous to the learner due to the safe training environments the simulations provided. More recently, these training environments have proven beneficial in the transfer of user-learned skills from the simulated environment to the real world [5, 31, 48, 51, 57]. Of course the VR technology of today has come a long way. Contemporary displays boast high-resolution, wide-angle fields of view and increased portability. This has led to the evolution of new VR research and training applications in many different arenas, several of which are covered in other chapters of this book. This is true of clinical assessment and rehabilitation as well, as the field has recognized the potential advantages of incorporating VR technologies into patient training for almost 20 years [7, 10, 18, 45, 78].

Keywords: Assessment | Dynamical Disease | Functional Mobility | Rehabilitation | Tunnel vision | Virtual Environment | Locomotion | Virtual Therapy

Chapter:

The advent of virtual reality (VR) as a tool for real-world training dates back to the mid-twentieth century and the early years of driving and flight simulators. These simulation environments, while far below the quality of today's visual displays, proved to be advantageous to the learner due to the safe training environments the simulations provided. More recently, these training environments have proven beneficial in the transfer of user-learned skills from the simulated environment to the real world (e.g., [5, 31, 48, 51, 57]). Of course the VR technology of today has come a long way. Contemporary displays boast high-resolution, wide-angle fields of view and increased portability. This has led to the evolution of new VR research and training applications in many different arenas, several of which are covered in other chapters of this book. This is true of clinical assessment and rehabilitation as well, as the field has recognized the potential advantages of incorporating VR technologies into patient training for almost 20 years (e.g., [7, 10, 18, 45, 78]).

Many of the early desktop VR clinical interventions unfortunately suffered from technological constraints that limited their value as training tools for clinical populations. In particular, they often required patients to remain stationary (seated or standing) and interact with displays on a computer monitor. Recently, however, new technological advances that allow the user to navigate virtual environments by walking (either over ground or on a treadmill), combined with the steady improvement of visual displays, serve to enhance the immersive nature of VR and introduce new behavioral measurement opportunities. As a result, we are in the midst of a paradigm shift in rehabilitation science; the field is beginning to move away from predominantly stationary interventions viewed on a computer monitor and toward dynamic, interactive user-controlled virtual environments. The impact of this shift has been intensified by emergent technologies such as the *Nintendo Wii* (Nintendo Co. Ltd., Kyoto, Japan) and *Microsoft Kinect* (Microsoft Corp., Redmond, Washington) systems as well. These systems, and others like them, have led to the widespread cost-effective availability of interactive VR and may provide new opportunities for the application of VR interventions both inside the home and in local clinical settings. All of these technological enhancements have potentially far-reaching implications for clinical assessment and rehabilitation and, accordingly, serve as the impetus for this chapter.

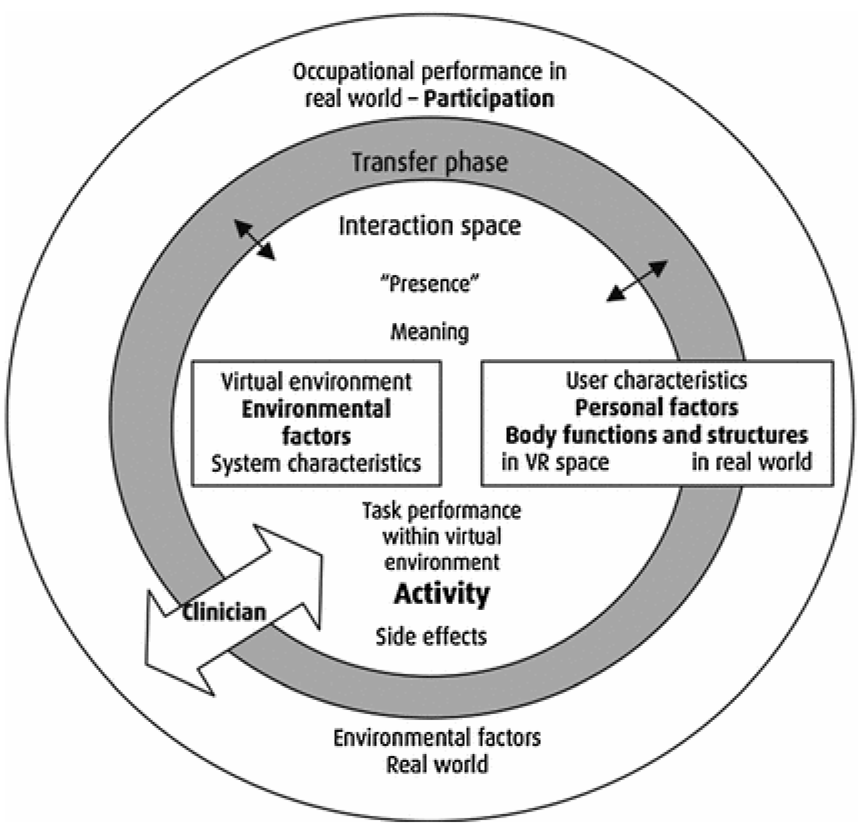

Figure 15.1. The three-nested *circle* schema. Reproduced with permission (A request of permission for reproduction of this figure was submitted in the Fall of 2011.) from Weiss et al. [74]

One of the primary advantages of VR is that it provides a platform for the development of unique and customizable interventions that are not available or easily implemented in the real world. Specifically, VR enables the manipulation of training duration, intensity and feedback to satisfy clinical demands for intensive and repetitive patient training [9].[1] When developing VR interventions, it is important to consider both the construction of the virtual environment and the interfaces for measurement and feedback that accompany them. A useful framework to guide the development of VR-based rehabilitation was introduced by [74] in the form of a nested three-circle schema in Fig. 15.1. The schema represents the VR-based rehabilitation process as it relates to the patient, with the three circles illustrating each component of this process (listed in order from inner to outermost): (1) the interaction space, (2) the transfer phase, and (3) the real world.

The inner circle, or *interaction space*, signifies the interface between the user and the virtual environment. The user's characteristics (e.g., age and anthropometrics), function (e.g., sensory and mobility deficits) and the targeted anatomical structures engaged during the task all contribute to the user's interaction with the virtual world [75]. This allows for a VR intervention that is aligned with the user's real world experiences and results in a natural task environment with adequate visual and idiothetic information.[2] Further, the realism and ecological validity of VR environments is important to the enhancement of training efficiency in VR-based rehabilitation [17]. The middle circle, or band, represents the *transfer phase* and refers to the transferability of learned skills from the virtual environment (i.e., interaction space) to the real world. This phase requires varied levels of clinician support and training time depending on the severity and type of disability facing the patient [26]. It may even require combining virtual imagery with the real world (e.g., augmented reality)[3] to facilitate or catalyze skill transfer, in order to promote improved daily function. The final, outermost circle in the schema refers to the *real world* and denotes changes in the affordances of the environment [15, 65] as a result of rehabilitation. For example, objects that previously prevented patients from interacting with the real world—the presence of low curbs or moving obstacles in a crowded environment (e.g., a busy airport or a busy intersection)—no longer present barriers but now afford passage for walking. This component is wholly dependent on the skills gained in the transfer phase and symbolizes the final rehabilitation goal of increasing the patient's participation in the real world, ultimately leading to an improved quality of life [75].

The nested three-circle schema introduces a useful heuristic for the development and implementation of immersive VR-based rehabilitation interventions. Moreover, each individual component highlights important considerations for researchers and clinicians as they seek to employ these techniques in patient populations. The rest of this chapter is devoted to reviewing different VR-based approaches to rehabilitation and assessment. Each of these approaches is distinguished by novel methodologies developed by clinicians and researchers alike. Despite these differences, each method shares a commitment (whether intentional or not) to the principles of the three-circle schema and offers a framework, in its own right, for the development of new and exciting VR-based interventions for improving functional mobility.

15.1 VR-Based Assessment and Rehabilitation to Promote Functional Mobility

A person's mobility depends on an adaptively functioning perception-action system. Consequently, mobility limitations can arise from a host of pathologies and injuries that affect various loci in this system, from sensory receptors to cortical areas to musculo-skeletal components. However, such deficits typically impact the function of the system as a whole, and require adaption of perceptual-motor control strategies. For example, a chronic knee injury may alter the actions afforded by the environment and require the remapping of visual information to gait control variables in order to generate adaptive locomotion. Rehabilitation may thus not only involve strengthening muscles and retraining motor patterns, but relearning whole perceptual-motor control relations.

The ensuing mobility deficits may persist indefinitely and often deteriorate over time. For instance, at 12 months post-stroke, patients suffering from hemiplegia exhibit motor deficits in the form of longer gait cycles with decreased cadences, and this results in a 50 % reduction in walking speed compared to the gait patterns of unaffected control participants [38, 63]. Patients suffering from Parkinson's disease frequently exhibit *freezing gait*—a term that encompasses both the inability of the patient to initiate or sustain a walking gait, and shuffling forward with small steps as their legs exhibit muscle trembling—and these symptoms worsen as the disease progresses [6, 44]. Mobility issues are also the typical sequelae of sensory deficits such as "tunnel vision" due to conditions like retinitis pigmentosa (RP)—a group of hereditary disorders characterized by retinal pigmentary degeneration that often leads to progressive visual field loss [13, 22, 27, 32, 58]. This spectrum of deficits detracts from a patient's functional mobility by reducing their ability to adapt (prospectively and/or reactively) to normally varying environmental conditions during locomotion. Moreover, their physiological basis influences the type and severity of the deficit, as well as the type of intervention that can be utilized to improve patient mobility. In direct response to these problems, researchers have started to employ VR training interventions that focus on increasing the walking speed and adaptability of patients with mobility deficits [11, 24, 36]. Others have developed unique VR assessment protocols that exploit the flexibility of VR and may have potential advantages over real-world clinical assessments [12, 28].

15.1.1 VR-Based Assessment and Rehabilitation Following Motor Dysfunction

One of the unique capabilities of VR is that optical information can be enhanced or manipulated during ongoing walking. For example, *optic flow*—the pattern of motion available from the ground and background surfaces during locomotion [14, 67]—provides information about one's speed and direction of travel (or *heading*). The rate of optic flow has been shown to influence the perceived speed of participants and to elicit changes in walking speed [37, 40, 43, 62]. Similarly, shifting the pattern of optic flow to the left or right influences the perceived heading direction [70], and elicits compensatory postural [3, 69] and steering adjustments when walking to a goal [59, 68]. Using VR to manipulate optic flow thus has the potential to alter the interaction space and provide salient information about locomotion speed and heading to the patient.

Lamontagne et al. [28] used such a manipulation to examine the perceptual-locomotor adaptability of patients suffering from post-stroke hemiplegia. During two experiments patients and unaffected control participants walked on a human-driven treadmill while virtual corridors provided optic flow information through a head-mounted display (HMD). The first experiment required participants to walk at a comfortable speed as the optic flow rate was varied continuously in an open-loop sinusoidal pattern at 0.017 Hz. This resulted in a compensatory out-of-phase relation between gait and optic flow speed for all participants (i.e., participants walked faster during slower optic flow conditions and vice versa),[4] although this was less pronounced for the patients and their phase relation was much more variable. In the second experiment the walking speed of participants during a baseline optic flow trial (1:1 mapping between walking pace and optic flow) was compared to their walking speed in a series of trials in which optic flow was discretely manipulated above or below the comparison trial. Again, walking speed was inversely related to rate of optic flow, but the patients were equal to the healthy controls in their gait response to optic flow. Taken together, the results of these two experiments provide evidence that patients with hemiplegia following stroke are influenced by optic flow in a similar way to healthy controls. This indicates, preliminarily, that virtual optic flow might be useful in training these patients to increase their walking speed over the course of a training intervention.

VR has also been used to manipulate visual cues to modulate the gait characteristics of patients with Parkinson's disease through both continuous optic flow (e.g., [49]) and continuous information paired with discrete visual stimuli (e.g., [60]). Similar to Lamontagne et al. [28], Schubert et al. required patients with Parkinson's disease and control participants to maintain a preferred walking speed on a human-driven treadmill while they viewed an optic flow pattern that varied at a constant speed perceived to be either faster or slower relative to the preferred walking speed of each participant. The results indicated that the patients with Parkinson's disease were more susceptible to changes in optic flow speed (i.e., their preferred walking speed was more variable) compared to control participants. The researchers concluded that the patients were more reliant on visual information, perhaps due to their decreased ability to utilize proprioceptive information, which resulted in impaired adaptation to optic flow.

The work of van Wegen et al. [60] expanded on the optic flow approach by introducing various discrete stimuli into optic flow scenarios. Specifically, they required Parkinson's patients and control participants to walk on an automatic treadmill while they viewed a virtual corridor (synchronized with the treadmill speed) displayed on a screen in front of them. Two conditions required participants to walk in front of a blank screen in the presence or absence of a rhythmic temporal cue (i.e., a flashing light that patients viewed while wearing a pair of glasses). Three additional conditions consisted of the virtual corridor either by itself or in combination with either the temporal cue or a spatial cue (i.e., transverse lines overlaid on top of the virtual corridor). Both the spatial and temporal cues lowered the patients' stride frequency even as they were able to maintain their walking speed, but this may have been due to the visual cues drawing the attention of patients to the walking pattern [60]. Interestingly, the virtual corridor did not have an effect when compared to the non-VR conditions. Here the automaticity of the treadmill may have washed out any potential contributions the virtual corridor might have had on the patients' gait patterns, particularly given the effects observed on a human-driven treadmill by Lamontagne et al. [28].[5] Regardless, the results of van Wegen et al. provides preliminary evidence that the rigid gait patterns of patients with Parkinson's disease are not tightly coupled to walking speed and may be manipulated by visual cues. Thus, VR-based rehabilitation may hold promise for training these types of patient populations.

Experimenters have also utilized VR to simulate patient interactions with the real world to promote successful obstacle avoidance and circumvention. This is done through either the use of virtual obstacles during patient testing or in the evaluation of the transfer of VR training to real world obstacles. Moreover, these methods can be utilized in conjunction with modified perceptual information (e.g., optic flow), or separately. For example, Fung et al. [11] conducted a feasibility study of two patients post-stroke. Three separate virtual environments (i.e., a corridor, a park and a street crossing) were viewed on a screen while each patient walked on a feedback-driven motorized treadmill. As each patient successfully traveled these environments, the task difficulty increased by requiring faster walking speeds in order to successfully avoid virtual collisions. They were also forced to cope with increasing surface slope changes on the treadmill. Patients were able to increase their walking speed and maintain that speed in the face of slope changes. However, these mobility improvements did not translate to improved virtual obstacle avoidance by either patient. The nature of this feasibility study limits its generalizability, for the researchers did not test a control group or a comparison group that trained in a real environment. Therefore, it is difficult to separate general training effects from specific effects of the virtual interventions. Nonetheless, the results hold promise for the viability of VR as a training tool in comparable walking scenarios.

Jaffe et al. [24] examined a similar cohort of patients as they walked on a motorized treadmill while stepping over virtual obstacles, and vibrotactile sensations were used to provide feedback when contact was made with an obstacle. Patient performance in VR was then compared to the performance of a separate group of patients who trained on a 10 m walkway in the real world while stepping over actual obstacles. The patients that were trained in VR exhibited increases in walking speed (in a separate fast walk test) compared to the patients who trained in the real world. The researchers suggested that the visual augmentation of the virtual obstacles combined with the enhanced safety of the VR intervention were contributors to these improvements. It is also possible that the treadmill forced participants to maintain their walking speed leading up to, and following, obstacle clearance, and that the absence of this in the over-ground walking conditions influenced patient improvement as well.

More recently, Mirelman et al. [36] examined the influence of a similar VR intervention on the gait characteristics of patients with Parkinson's disease, compared to previously collected data from an historical active control group. The training required patients to walk on a virtual path (via a treadmill) as they coped with visual distracters (i.e., moving objects and changes in environmental lighting) while negotiating obstacles of varying size and frequency. Both treadmill speed and visual complexity of the environment were increased as patient performance improved over six weeks of training. Gait characteristics were assessed prior to and after the VR intervention by testing patients during three real-world walking conditions: (1) walking over ground, (2) walking while stepping over real world obstacles, and (3) walking while performing a concurrent mental task. The real-world tests revealed an increase in walking speed during all three of the evaluation conditions, with retention effects present up to a month after the final training session. These results are perhaps the most promising to date because they demonstrate that patient improvements, trained in certain VR contexts, are retained by the patients for a substantial period of time outside of VR.

15.1.2 VR-Based Assessment and Rehabilitation Following Visual Dysfunction

In some cases, mobility problems are consequences of local deficits in the early visual system. One of the consequences of visual disorders such as retinitis pigmentosa (RP) or choroideremia—the latter a degeneration of the choroid and retina—is that patients suffer peripheral visual field loss (PFL), or tunnel vision. This makes it hard to see stationary and moving obstacles and obstructions, including other pedestrians. The problem is magnified when patients are faced with an unfamiliar setting, so even simple locomotor tasks can become very challenging, and increase the risk of trips, collisions or falls.

Li et al. [29] found that tunnel-vision patients can judge their heading from optic flow as accurately as age-matched controls, under free fixation conditions. However, Turano et al. [59] reported that RP patients have more difficulty judging their direction of heading relative to objects in the scene. To compensate for this limitation, patients employ an active scanning strategy in which they make a rapid sequence of fixations between objects, the floor ahead, and other features of the layout (e.g., [58]). This is different from normally sighted individuals who tend to focus their gaze in the direction of heading or toward the current goal. While an active scanning strategy may improve the perception of heading with respect to a known object, its effect on the detection of stationary and moving obstacles and the likelihood of collisions is unknown. For this reason, different assessment and training interventions are needed to understand the cost-benefit tradeoff of such a strategy and to develop new or improved strategies for enhanced mobility safety.

Given the nature of VR as a safe testing and learning environment, a group of researchers at the Schepens Eye Research Institute (Boston, MA) have conducted a pair of experiments with two specific objectives: they assessed VR as a viable tool for studying the mobility of patients with PFL and they explored the viability of studying visual-motor learning in surrogate patients by simulating PFL in normally-sighted participants [1, 33]. Apfelbaum et al. [1] examined the influence of different approach angles to a virtual obstacle on perceptual judgments of whether their path would pass to the right or left of the obstacle. The experimental setup consisted of a human-driven treadmill facing a projection screen displaying a passive VR model of a local shopping mall (i.e., not coupled to participant's eye or head positions). Patients with PFL (the mean field of view was equal to 5.9∘5.9∘ for the patient group) and control participants with an artificially reduced field of view (matched to the patient group) either passively viewed or actively walked while viewing the display (in passive viewing patients remained standing as the virtual environment moved). In this experiment all participants viewed the virtual environment monocularly while they approached the obstacle at different heading angles (ranging from 4∘4∘ to 20∘20∘, with 0∘0∘ representing a straight on approach). Both the control participants and the patients with PFL were equally accurate in their judgments and made judgments at similar distances from the obstacle. Additionally, when patients approached the obstacle at small angles while walking their accuracy increased, in contrast to an opposite pattern of results from the control participants. Both groups delayed their responses when walking until they were closer to the virtual obstacle than in passive viewing, suggesting that a walking-based VR interface might be important for evoking perceptually guided behavior that generalizes to the real world [1]. We are currently collaborating with the Schepens group to investigate the detection and avoidance of stationary and moving obstacles by PFL patients during overground walking in immersive VR [25].

Luo et al. [33] continued this line of research while employing the Multiplexing Vision Rehabilitation Device (cf. [41]).[6] Using the same experimental set-up as the previous experiment, participants interacted with the virtual environment through either a minified view or a normal view across different conditions. The goal was to make sure the multiplexing device did not cause individuals to overestimate collision risks during active walking or passive viewing. The perceived passable space around the obstacle and variability of collision judgments were both greater for patients than for normally sighted participants during simulated walking (i.e., passive viewing), absent the minified device. The collision judgments were also more accurate for the normally sighted controls during the walking condition. Consequently, the minified device had no effect on the patients with PFL or the controls during either condition. These findings indicate that while the multiplexing device did not degrade performance in either population—an important finding given the increased attentional demands imposed by the device—it also did not improve perceptual judgments of collisions in the virtual environment.

These two experiments demonstrate the advantages of VR-based assessment of patients suffering from visual disorders. Specifically, important research questions about obstacle avoidance can be investigated without risk of injury to patients. In addition, VR enables simulation environments that mimic pathological deficits in healthy participants. This helps to ease the burden of participation by the clinical populations while researchers can draw from a large participant pool. While more research is necessary to ensure the viability of approaches such as these, these two experiments provide a solid foundation for exploring similar types of questions.

15.2 Dynamical Disease and VR-Based Assessment

Up to this point we have reviewed research associated with new developments in rehabilitation science sparked by interactive, immersive virtual environments. Over the last 30 years, clinical assessment has been undergoing another, equally important shift in thinking—the emergence of the concept of *dynamical disease* and techniques to measure it (see Van Orden [61], and West [76], for reviews). Dynamical disease, broadly defined, involves a physiological control system operating within parameter ranges that constrain the system's dynamics in such a way that it generates pathological behavior [16, 34]. This shift challenges the premise that behavioral variability is adverse to healthy functioning—a prominent assumption in clinical locomotor research (e.g., [4, 19, 39, 52, 64, 73]). A central tenet of this approach is that the system's dynamics, indexed by continuous measurement of locomotor patterns, are more revealing than classic summary statistics alone. For example, healthy adult gait exhibits a movement signature that is altered by neurological insult due to injury, aging, or disease [20, 54]; a difference that is not adequately captured by the mean and variance of behavior. The question of how one should measure the system dynamics, specifically how to quantify the patterns of variability in gait measures, is now at the forefront of clinical assessment research.

Virtual reality has the potential to play an important role in this transformation, for it enables the control of information that could influence the dynamics of movement [66]. This offers the flexibility to manipulate visual stimuli during walking in an attempt to alter the pattern of variability exhibited by the individual's gait cycle (e.g., [47]). VR can also be used to manipulate the locomotor trajectory of patients during over-ground walking (e.g., [12]). In other words, VR can be used to modify control parameters, thereby allowing researchers to test specific predictions about the role of those parameters in clinical assessment. These behaviors are a result of complex interactions at various control levels. Consequently, the examination of the various control parameters must take place at multiple scales of observation to fully understand the system dynamics. The remainder of this chapter will focus on several novel VR applications for the assessment of functional mobility at the level of the gait cycle and the level of the locomotor trajectory.

15.2.1 Dynamic Measures for Assessing Local Functional Mobility Using VR

Synchronizing to a stimulus is an experimental method commonly used to influence the timing properties of motor behavior. For example, much like the van Wegen et al. [60] study in which visual cues were employed to influence the step frequency, and consequently the mobility, of patients with Parkinson's disease, rhythmic auditory stimulation with a metronome has been used to improve the mobility of these patients as well [30, 35, 56, 77]. The perceptual-motor differences between synchronizing to an auditory versus a visual metronome have been described elsewhere [23], but it remains unclear which is optimal for purposes of assessment and rehabilitation. Recently, it has been demonstrated that more efficient adaptation to a perturbation (i.e., visual or auditory disruption of the stimulus rhythm) occurs when elderly participants synchronize to a visual stimulus [2]. This finding provides evidence for the privileged role visual information seems to play in the modification of acute changes to the gait cycle in healthy elderly adults. Given the biological nature of human gait, however, synchronizing to a metronome with fixed time intervals may not be effective in facilitating adaptive gait patterns and enhancing functional mobility.

Variability in the gait cycle, once thought to be a random by-product of biological noise, is now believed to reflect adaptive, functional gait (c.f., [20, 54]). Specifically, the variation in the stride-to-stride time intervals of healthy adults exhibits scale invariant (fractal) temporal correlations, as indexed by detrended fluctuation analysis (DFA[7]; [21]). Accordingly, asking a patient to synchronize to a metronome having fixed time intervals may actually reduce this natural variation, interfering with functional gait. Conversely, if humans can synchronize to a variable, or "noisy", visual metronome, this may enhance adaptive variation in their gait. A noisy metronome produces irregular intervals—some are shorter and some are longer than the previous one. A fractal pattern of dynamic variability can be generated to mimic those observed in healthy human gait. Instructing a patient to synchronize to a fractal metronome might induce desired patterns of dynamic variability in their gait cycle, enhancing adaptive functional mobility.

Evidence that participants can synchronize to a noisy visual metronome was first observed in finger tapping [53]. A flashing square on a computer screen prescribed the inter-tap intervals for the participant. The long-range correlations of the visual metronome intervals (indexed by DFA) were manipulated between conditions, and the participants' inter-tap intervals were shown to exhibit the same long-range correlations as the visual metronome. This provided evidence that the structure of variability of a movement task could be manipulated by altering the dynamic properties of a visual stimulus.

We recently extended this methodology to the gait domain to determine whether similar shifts in gait dynamics could be elicited in a desired direction [47]. Participants synchronized their steps to a flashing square on a computer screen while walking on a treadmill. The visual metronome generated intervals with a variety of long-range temporal correlations (indexed by DFA), yielding either a more "fractal" metronome (with a more correlated pink noise structure) or a more "random" metronome (with a more decorrelated white noise structure). The stochastic variability in participants' stride-to-stride intervals correspondingly shifted in the prescribed direction, from a normal pink noise pattern toward a more fractal pattern or a more random pattern, respectively. This result provides a proof-of-concept for the efficacy of using noisy visual metronomes to manipulate the nonlinear dynamics of the gait cycle. The exciting possibility is that this effect might be harnessed clinically to enhance adaptive gait and functional mobility.

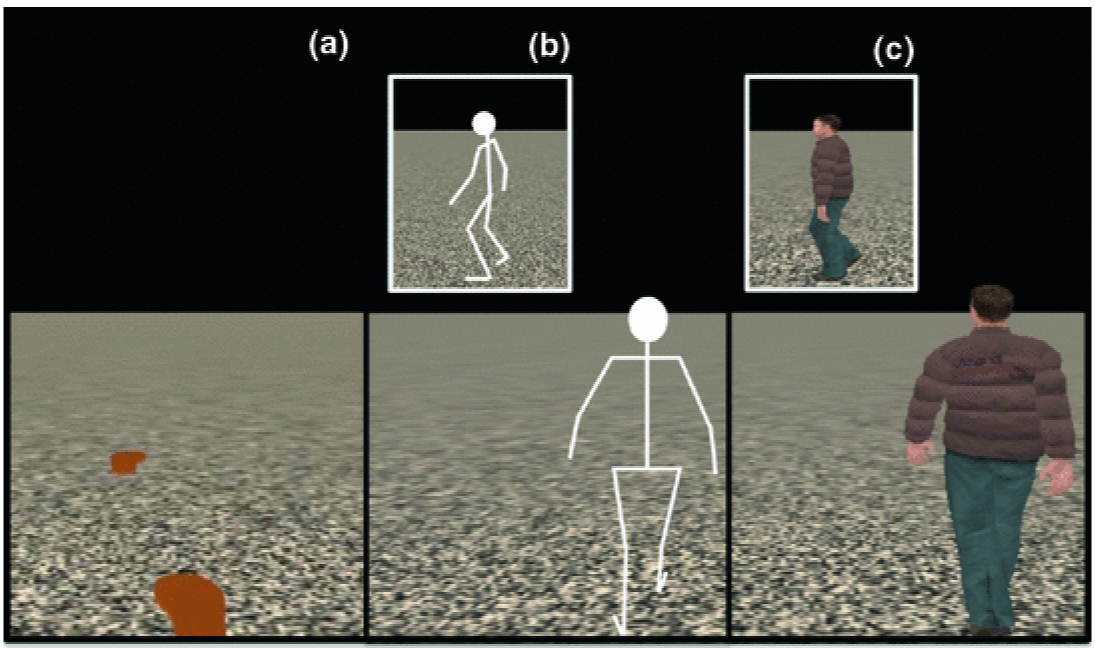

Figure 15.2. Representation of a sample display of **(a)** virtual footprints, **(b)** a stick figure, and **(c)** a virtual human to be used as visual cues to modify the gait patterns of patients

It should be noted that visual stimuli can be presented continuously as well as discretely. A discrete visual stimulus (i.e., a classic visual metronome) only prescribes the time when an event should occur (e.g., a heel-strike during locomotion). A continuous visual stimulus, on the other hand, provides information that anticipates and specifies the timing of the upcoming event (e.g., motion of the foot and/or limb leading to and including a heel-strike). While a discrete stimulus has been shown to be useful, a continuous stimulus might enable a participant to more precisely synchronize to irregular events. VR has the potential to present novel classes of stimuli, such as virtual humans and avatars[8] that provide continuous information. It is therefore possible to imagine a number of ways that continuous information about the desired gait pattern could be presented to a patient. For example, footprints could appear discretely on the ground plane in a virtual environment, providing visual information about the timing leading up to heel-strike (see Fig. 15.2a). A stick figure could walk through a virtual landscape, providing information to the patient about joint angles in the different phases of the gait cycle (see Fig. 15.2b). It is possible that a humanoid figure would be even more salient for synchronization purposes, so high-definition virtual humans or avatars may be an appropriate choice (see Fig. 15.2c). Finally, a third-person display of dual figures could be presented: the desired movement might be specified by a virtual human driven by a computational model or an avatar driven by motion capture data, while visual feedback is provided by an avatar yoked to the patient. This scenario would not only give the patient immediate feedback about their own performance, but would provide a model character for on-line movement comparison. Investigations into these types of stimuli are currently underway in the Virtual Environment for Assessment and Rehabilitation Laboratory (VEAR Lab) at the University of North Carolina at Greensboro.

15.2.2 Dynamic Measures for Assessing Global Functional Mobility Using VR

The previous examples illustrate the potential strength of VR applications for rehabilitation; namely, the opportunity to manipulate environmental information to probe the control parameters and index the dynamics of functional mobility at the local level of the step cycle. VR also lends itself to the flexible design of assessment protocols that yield continuous measures of behavior at a more global level, such as the locomotor trajectory.

Consider the problem of evaluating the functional mobility of patients with a knee injury—a tear in their anterior cruciate ligament (ACL)—before and after surgery. Functional mobility in the real world subjects the knee joint to a wide range of forces and torques at various joint angles and velocities and with various patterns of muscular co-contraction, which are not currently measured in a clinical assessment. We are beginning to develop a battery of functional mobility tasks that exploit the flexibility of ambulatory VR to manipulate the affordances of the environment and capture the natural range of variability in an assessment context. Tests may include turns of varying curvature, quick stops and sharp reversals, stepping over gaps of varying widths, stepping up or down through various heights, and so on.

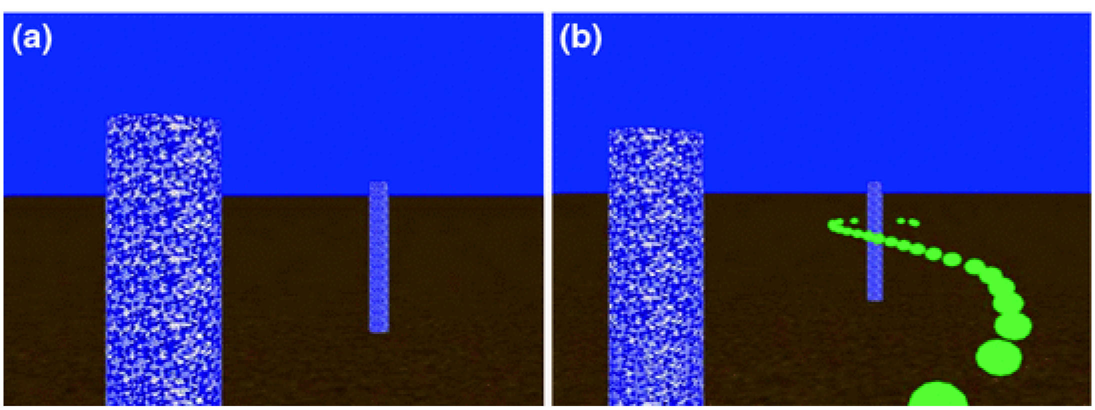

Figure 15.3. Example displays from the baseline/controlled speed (**a**) and controlled path (**b**) conditions similar to those used in the figure-8 experiment conducted by Gerin-Lajoie et al. [12]

As a first step, Gérin-Lajoie et al. [12] developed an over-ground walking task in a virtual environment that varied the path's radius of curvature, to assess the impact of an emulated knee disability on the locomotor trajectory. Participants wearing an immobilizing knee splint walked in a figure-8 path around two virtual poles 6 m apart. There were three VR conditions: (1) natural walking at a self-selected pace, (2) speed-controlled walking, in which auditory feedback prompted participants to maintain a speed at or above their natural walking pace, and (3) path-controlled walking, in which participants followed virtual markers while receiving performance-based auditory feedback (Fig. 15.3). The participant's trajectory was then assessed to identify gait impairment indicators, and revealed a trade-off between path curvature and walking speed. Specifically, participants with an immobilized knee either decreased their speed to maintain path geometry, or increased their path radius to maintain walking speed, compared to the controls.

In addition, for the first time we exploited nonlinear dynamical methods to analyze the structure of variability at the level of the locomotor trajectory. Recurrence quantification analysis (RQA)[9] of the heading direction provided several measures of repeating temporal patterns in the trajectory as a participant walked the figure-8 path. These measures also differentiated the two groups, revealing that locomotor trajectories with an immobilized knee were less repeatable, less stable over time, and less mathematically complex than with a normal knee [46]. We are currently in the midst of a longitudinal study that uses the figure-8 task to assess the functional mobility of patients with actual ACL injuries pre- and post-surgery, with a follow-up after rehabilitation [50].

This research illustrates the possibilities offered to clinicians by VR-based assessment and rehabilitation. It takes advantage of perceptual manipulations that are unique to VR and allows for dynamic measurements of changes in functional locomotor behavior. Such work suggests the potential future of VR-based assessment and rehabilitation.

15.3 Conclusion

It should be clear by now, based on the numerous VR methodologies presented in this chapter, that one of the major challenges facing VR-based assessment and rehabilitation is determining the type of VR installation to employ. The visual display and head tracking devices available, as well as systems for kinematic and kinetic measurement of movement, strongly constrain the type of locomotor behavior permitted. For example, whether the user traverses the virtual environment by walking over-ground, walking on an omni-directional or linear treadmill, or via some other Wii or Kinect interface, and whether the treadmill is human- or motor-driven, have important implications for mobility assessment. Over-ground walking allows for the most natural interaction between the user and the virtual environment, implying good validity and generalizability, but such systems are expensive and space limitations often constrain them to a small room. Motorized or human-driven treadmill systems allow virtual environments of almost unlimited size, but at the price of less natural navigation (e.g., restricted turns, unnatural acceleration or deceleration) and possibly reduced validity and generalizability. Although such sophisticated technology may find a place in a regional hospital or research setting, simple Wii and Kinect-based applications have the potential for greatest impact on rehabilitation in the living room. Accordingly, researchers and clinicians must carefully consider their options when adopting these technologies and recognize the potential limitations for VR-based assessment and rehabilitation.

Regardless of these issues, the pursuit of VR-based assessment and rehabilitation is likely to increase in the coming years, as the potential benefits offered by these systems outweigh their shortcomings. It is still too early to tell whether the promise of VR will ultimately pay off for rehabilitation science, but with almost limitless possibilities awaiting implementation the future looks very bright.

Footnotes

1. It is important to note that there are two different applications of VR in rehabilitation. When VR is used as an adjunct to rehabilitation, it is typically referred to as VR-augmented rehabilitation. Conversely, VR provided alone as a rehabilitation intervention is referred to as VR-based rehabilitation [8]. The latter is the predominant focus of this chapter.

2. If the visual and idiothetic information are not aligned with the user's actions a disruption of the user's sense of realness, or *presence*, in the virtual environment can result, leading to feelings of physical disorientation and even nausea [55].

3. Augmented reality is a tool in which the virtual world is superimposed over the real world, with the virtual information serving as a supplement to what is available in the real world alone [17].

4. The relation between optic flow and gait speed has been studied extensively (see text). While the findings of Prokop et al. [43] and Mohler et al. [37] parallel those of Lamontagne et al. [28], it is unclear why, exactly, the out-of-phase relation was observed. One possibility, as suggested by the authors, is that a sinusoidal change in optic flow speed may lead to a more pronounced time lag between the change in stimulus and the behavioral response. Another is that when the flow rate decreases, the participant walks faster to compensate for a perceived decrease in speed, in order to maintain a constant or preferred speed [37].

5. This is based on a variation of the posture-first principle [79] in which participants would prioritize locomotion on the treadmill over attending to the perceptual information on the screen in front of them.

6. The Multiplexing Vision Rehabilitation Device is an augmented reality device in which the user wears a see-through head-mounted display (HMD) with a 25∘25∘ field of view to which a small monochrome video camera has been attached. When wearing the device the user not only sees the real world in full resolution, but also sees real-time edge detection from a field of view between 75∘75∘ and 100∘100∘, minified and displayed on the smaller field of view provided by the HMD [41].

7. DFA computes scaling exponents that relate a measure of variability, the detrended fluctuation function, to the time scale over which the function was computed. It is used to identify the presence or absence of persistence (i.e., a large value tends to follow a large value and a small value tends to follow a small value) in a time series. For full details, see Peng et al. [42].

8. A distinction must be made about the origin of the continuous information. If a computer algorithm drives the character in virtual reality, then it is presenting continuous information about walking biomechanics that is non-biological and is termed a virtual human. Alternatively, the character can be driven by the actual motion of a human in either real-time or via a recording,

which is deemed biological motion and termed an avatar. Current literature has not made a distinction about which type of motion is optimal for a gait synchronization task.

9. RQA is a nonlinear measure that indexes repeating, or recurrent, patterns in a time series. For a review see Webber and Zbilut [71, 72].

References

1. Apfelbaum H, Pelah A, Peli E (2007) Heading assessment by "tunnel vision" patients and control subjects standing or walking in a virtual environment. ACM Trans Appl Percept 4:1–16

2. Bank PJM, Roerdink M, Peper CE (2011) Comparing the efficacy of metronome beeps and stepping stones to adjust gait: steps to follow. Exp Brain Res 209:159–169

3. Bardy BG, Warren WH, Kay BA (1996) Motion parallax is used to control postural sway during walking. Exp Brain Res 11:271–282

4. Blin O, Ferrandez A, Serratrice G (1990) Quantitative analysis of gait in Parkinson patients: increased variability of stride length. J Neurol Sci 98:79–91

5. Bliss JP, Tidwell PD, Guest MA (1997) The effectiveness of virtual reality for administering spatial navigation training to firefighters. Presence: Teleoperators Virtual Environ 6:73–86

6. Bloem BR, Hausdorff JM, Visser JE, Giladi N (2004) Falls and freezing of gait in Parkinson's disease: a review of two interconnected, episodic phenomena. Mov Disord 19:871–884

7. Brooks B, McNeil JE, Rose FD (1999) Route learning in a case of amnesia: a preliminary investigation into the efficacy of training in a virtual environment. Neuropsychol Rehabil 9:63–76

8. Burdea GC (2003) Virtual rehabilitation—benefits and challenges. Methods Inf Med 42:519–523

9. Deutsch JE, Mirelman A (2007) Virtual reality-based approaches to enable walking for people poststroke. Topics Stroke Rehabil 14:45–53

10. Emmett A (1994) Virtual reality helps steady the gait of Parkinson's patients. Comput Graph World 17:17–18

11. Fung J, Richards CL, Malouin F, McFadyen BJ, Lamontagne A (2006) A treadmill and motion coupled virtual reality system for gait training post-stroke. CyberPsychol Behav 9:157–162

12. Gerin-Lajoie M, Ciombor DM, Warren WH, Aaron RK (2010) Using ambulatory virtual environments for the assessment of functional gait impairment: a proof-of-concept study. Gait Posture 31:533–536

13. Geruschat DR, Turano KA, Stahl JW (1998) Traditional measures of mobility performance and retinitis pigmentosa. Optom Vis Sci 75:525–537

14. Gibson JJ (1950) The perception of the visual world. Houghton Mifflin, Boston

15. Gibson JJ (1979) The ecological approach to visual perception. Houghton Mifflin, Boston

16. Glass L, Mackey MC (1979) Pathological conditions resulting from instabilities in physiological control systems. Ann N Y Acad Sci 316:214–235

17. Gobbetti E, Scatenis R (1998) Virtual reality: past, present and future. In: Riva G, Wiederhold BK, Molinari E (eds) Virtual environments in clinical psychology and neuroscience. Ios Press, Amsterdam, pp 1–18

18. Goldberg S (1994) Training dismounted soldiers in a distributed interactive virtual environment. U.S. Army Res Inst Newslett 14:9–12

19. Grabiner PC, Biswas ST, Grabiner MD (2001) Age-related changes in spatial and temporal gait variables. Arch Phys Med Rehabil 82:31–35

20. Hausdorff JM (2007) Gait dynamics, fractals and falls: Finding meaning in the stride-to-stride fluctuations of human walking. Hum Mov Sci 26:555–589

21. Hausdorff JM, Peng C-K, Ladin Z, Wei JY, Goldberger AL (1995) Is walking a random walk? Evidence for long-range correlations in stride interval of human gait. Model Physiol 78:349–358

22. Haymes S, Guest DM, Heyes A, Johnston A (1996) Mobility of people with retinitis pigmentosa as a function of vision and psychological variables. Optom Vis Sci 73:621–637

23. Hove MJ, Spivey MJ, Krumhansl CL (2010) Compatibility of motion facilitates visuomotor synchronization. J Exp Psychol: Hum Percept Perform 36:1525–1534

24. Jaffe DL, Brown DA, Pierson-Carey CD, Buckley EL, Lew HL (2004) Stepping over obstacles to improve walking in individuals with poststroke hemiplegia. J Rehabil Res Dev 41:283–292

25. Kiefer AW, Bruggeman H, Woods R, Warren W (2012) Obstacle detection during walking by patients with tunnel vision. J Vis 12:183

26. Kizony R, Katz N, Weiss PL (2004) Virtual reality based intervention in rehabilitation: relationship between motor and cognitive abilities and performance within virtual environments for patients with stroke. In: Proceedings of the 5th international conference on disability, virtual reality and associated technology. Oxford, UK

27. Kuyk T, Elliott JL, Biehl J, Fuhr PS (1996) Environmental variables and mobility performance in adults with low vision. J Am Optom Assoc 67:403–409

28. Lamontagne A, Fung J, McFadyen BJ, Faubert J (2007) Modulation of walking speed by changing optic flow in persons with stroke. J NeuroEng Rehabil 4:22–30

29. Li L, Peli E, Warren WH (2002) Heading perception in patients with advanced retinitis pigmentosa. Optom Vis Sci 79:581–589

30. Lim I, Wegen EV, Goede CD, Deutekom M, Nieuwboer A, Willems A, Kwakkel G (2005) Effects of external rhythmical cueing on gait in patients with Parkinson's disease: a systematic review. Clin Rehabil 19:695–713

31. Lintern G, Roscoe JM, Koonce JM, Jefferson M, Segal LD (1990) Transfer of landing skills in beginning flight simulation. Human Factors 32:319–327

32. Lovie-Kitchin JE, Mainstone JC, Robinson J, Brown B (1990) What areas of the visual field are important for mobility in low vision patients? Clin Vis Sci 5:249–263

33. Luo G, Woods RL, Peli E (2009) Collision judgment when using an augmented-vision head-mounted display device. Invest Ophthalmol Vis Sci 50:4509–4515

34. Mackey MC, Glass L (1977) Oscillation and chaos in physiological control systems. Science 197:287–289

35. McIntosh GC, Brown SH, Rice RR, Thaut MH (1997) Rhythmic auditory-motor facilitation of gait patterns in patients with Parkinson's disease. J Neurol Neurosurg Psychiatry 62:22–26

36. Mirelman A, Maidan I, Herman T, Deutsch JE, Giladi N, Hausdorff JM (2011) Virtual reality for gait training: can it induce motor learning to enhance complex walking and reduce fall risk in patients with Parkinson's disease? J Gerontol A: Biol Sci Med Sci 66A:234–240

37. Mohler BJ, Thompson WB, Creem-Regehr SH, Willemsen P, Pick HL et al (2007) Calibration of locomotion resulting from visual motion in a treadmill=based virtual environment. ACM Trans Appl Percept 4:1–17

38. Olney SJ, Richards C (1996) Hemiparetic gait following stroke. Part I: characteristics. Gait Posture 4:136–148

39. Owings T, Grabiner M (2004) Step width variability, but not step length variability or step time variability, discriminates gait of healthy young and older adults during treadmill locomotion. J Biomech 37:935–938

40. Pailhous J, Ferrandez A, Fluckiger M, Baumberger B (1990) Unintentional modulations of human gait by optical flow. Behav Brain Res 38:275–281

41. Peli E (2001) Vision multiplexing: an engineering approach to vision rehabilitation device development. Optom Vis Sci 78:304–315

42. Peng CK, Havlin S, Stanley HE, Goldberger AL (1995) Quantification of scaling exponents and crossover phenomena in nonstationary heartbeat time series. Chaos 5:82–87

43. Prokop T, Schubert M, Berger W (1997) Visual influence on human locomotion: modulation to changes in optic flow. Exp Brain Res 114:63–70

44. Riess TJ (1998) Gait and Parkinson's disease: a conceptual model for an augmented-reality based therapeutic device. In: Riva G, Wiederhold BK, Molinari E (eds) Virtual environments in clinical psychology and neuroscience. Ios Press, Amsterdam, pp 200–208

45. Riess TWS et al (1995) Augmented reality in the treatment of Parkinson's disease. In: Morgan K, Satava M, Sieburg HB (eds) Interactive technology and the new paradigm for healthcare. IOS Press, Amsterdam, pp 298–302

46. Rhea CK, Gérin-Lajoie M, Ciombor DMcK, Warren WH, Aaron RK, Recurrence quantification analysis of walking path trajectories in a functional mobility task with imposed constraints. In: Paper presented at the North American Society for Psychology in Sport and Physical Activity, Tucson, AZ

47. Rhea C, Kiefer A, Warren W, D'Andrea S, Aaron R (2011) Synchronizing to a "noisy" metronome induces corresponding shifts in fractal gait dynamics. In: Paper presented at the North American Society for Psychology in Sport and Physical Activity, Burlington, VT

48. Rose FD, Attree EA, Brooks BM (2000) Training in virtual environments: transfer to real world tasks and equivalence to real task training. Ergonomics 43:494–511

49. Schubert M, Prokop T, Brocke F, Berger W (2005) Visual kinesthesia and locomotion in Parkinson's disease. Mov Disord 2:141–150

50. Shalvoy RM, Bruggeman H, D'Andrea S, Warren W, Aaron RK (2013) Virtual environmental navigation to quantify functional disability in ACL-deficient knees. In: Paper presented at the Orthopedic Research Society, San Antonio, TX

51. Seymour NE, Gallagher AG, Roman SA, O'Brien MK, Bansal VK, Andersen DK, Satava RM (2002) Virtual reality training improves operations room performance. Ann Surg 236:458–464

52. Spaulding SJ, Livingston LA, Hartsell HD (2003) The influence of external orthotic support on the adaptive gait characteristics of individuals with chronically unstable ankles. Gait Posture 17:152–153

53. Stephen DG, Stepp N, Dixon JA, Turvey MT (2008) Strong anticipation: sensitivity to long-range correlations in synchronization behavior. Phys A 387:5271–5278

54. Stergiou N, Decker LM (2011) Human movement variability, nonlinear dynamics, and pathology: is there a connection? Hum Mov Sci 30:869–888

55. Tarr MJ, Warren WH (2002) Virtual reality in behavioral neuroscience and beyond. Nat Neurosci 5:1089–1092

56. Thaut MH, McIntosh C, Rice R, Miller RA, Rathbun J, Brault JM (1996) Rhythmic auditory stimulation in gait training for Parkinson's disease patients. Mov Disord 11:193–200

57. Torkington J, Smith SGT, Rees BI, Darzi A (2001) Skill transfer from virtual reality to a real laparoscopic task. Surg Endosc 15:1076–1079

58. Turano KA, Geruschat DR, Baker FH, Stahl JW, Shapiro MD (2001) Direction of gaze while walking a simple route: persons with normal vision and persons with retinitis pigmentosa. Optom Vis Sci 78:667–675

59. Turano KA, Yu D, Hao L, Hicks JC (2005) Optic-flow and egocentric-direction strategies in walking: central vs. peripheral visual field. Vis Res 45:3117–3132

60. van Wegen E, de Goede C, Lim I, Rietberg M, Nieuwboer A, Willems A, Jones D (2006) The effect of rhythmic somatosensory cueing on gait in patients with Parkinson's disease. J Neurol Sci 248:210–214

61. Van Orden GC (2007) The fractal picture of health and wellbeing. Psychol Sci Agenda 21. http://www.apa.org/science/psa/vanorden.html. Accessed 21 Sept 2008

62. Varraine E, Bonnard M, Pailhous J (2002) Interaction between different sensory cues in the control of human gait. Exp Brain Res 142:374–384

63. von Schroeder HP, Coutts RD, Lyden PD, Billings E, Nickel VL (1995) Gait parameters following stroke: a practical assessment. J Rehabil Res Dev 32:25–31

64. von Porat A, Henriksson M, Holmstrom E, Thorstensson CA, Mattsson L, Roos EM (2006) Knee kinematics and kinetics during gait, step and hop in males with a 16 years old ACL injury compared with matched controls. Knee Surg Sports Traumatol Arthrosc 14:546–554

65. Warren WH (1995) Constructing an econiche. In: Flach J, Hancock P, Caird J, Vicente K (eds) The ecology of human-machine systems. Erlbaum, Hilldsale, pp 210–237

66. Warren WH (2006) The dynamics of perception and action. Psychol Rev 113:358–389

67. Warren WH (2008) Optic flow. In: Basbaum AI, Kaneko A, Shepherd GM, Westheimer G (eds) The senses—a comprehensive reference: vision II (vol 2, Albright TD, Masland R, eds). Academic Press, Oxford, pp 219–230

68. Warren WH, Kay BA, Duchon AP, Zosh W, Sahuc S (2001) Optic flow is used to control human walking. Nat Neurosci 4:213–216

69. Warren WH, Kay BA, Yilmaz E (1996) Visual control of posture during walking: functional specificity. J Exp Psychol: Hum Percept Perform 22:818–838

70. Warren WH, Morris M, Kalish M (1988) Perception of translational heading from optical flow. J Exp Psychol: Hum Percept Perform 14:646–660

71. Webber CL, Zbilut JP (1994) Dynamical assessment of physiological systems and states using recurrence plot strategies. J Appl Physiol 76:965–973

72. Webber CL, Zbilut JP (2005) Recurrence quantification analysis of nonlinear dynamical systems. In: Riley MA, Van Orden GC (eds). Tutorials in contemporary nonlinear methods for the behavioral sciences. National Science Foundation, Arlington, pp 353–400. http://www.nsf.gov/sbe/bcs/pac/nmbs/nmbs.jsp. Accessed 28 Sept 2006

73. Webster KE, Merory JR, Wittwer JE (2006) Gait variability in community dwelling adults with Alzheimer disease. Alzheimer Dis Assoc Disord 20:37–40

74. Weiss PL, Kizony R, Feintuch U, Katz N (2006) Virtual reality in neurorehabilitation. In: Selzer ME, Cohen L, Gage FH, Clarke S, Duncan PW (eds) Textbook of neural repair and neurorehabilitation, vol 2. University Press, Cambridge

75. Weiss PL, Rand D, Katz N, Kizony R (2004) Video capture virtual reality as a flexible and effective rehabilitation tool. J Rehabil Res Dev 1:12

76. West BJ (2006) Where medicine went wrong: rediscovering the path to complexity. World Scientific Publishing Co. Pte. Ltd., Hackensack

77. Willems AM, Nieuwboer A, Chavret F, Desloovere K, Dom R, Rochester L, Wegen EV (2006) The use of rhythmic auditory cues to influence gait in patients with Parkinson’s disease, the differential effect for freezers and non-freezers, an explorative study. Disabil Rehabil 28:721–728

78. Wilson PN, Foreman N, Tlauka M (1996) Transfer of spatial information from a virtual to a real environment in physically disabled children. Disabil Rehabil 18:633–637

79. Woollacott M, Shumway-Cook A (2002) Attention and the control of posture and gait: a review of an emerging area of research. Gait Posture 16:1–14