



Walking on Virtual Tiles

YORAM BARAM¹, JUDITH AHARON-PERETZ²,
YAHALOMIT SIMIONOVICI³ and LIOR RON¹

¹*Department of Computer Science, Technion, Israel Inst. of Technology, Haifa, Israel.*
e-mail: baram@cs.technion.ac.il

²*Cognitive Neurology Unit, Department of Neurology, Rambam Medical Center, Haifa, Israel.*

³*Department of Industrial Engineering, Technion, Israel Inst. of Technology, Haifa, Israel.*

Abstract. This paper examines the application of virtual reality cues, generating the biofeedback effects of a real tiled floor, reported in [8], for gait improvement in Parkinson's Disease (PD) patients. A portable apparatus, comprising head and body-mounted 3-axis accelerometers, a wearable computer and see-through head-mounted display, creates a virtual tiled floor, responding to the patient's own dynamics. Performance of PD patients using the device improved (higher speed, longer stride) by about 30% on average.

Key words. movement disorders, Parkinson's disease, virtual reality

Introduction

Gait impairment is one of the main complaints of advanced Parkinson's Disease (PD) patients. Such patients often walk slowly with shuffling and dragging steps, reduced stride length, stooped posture and diminished arm swing [1,2]. Certain sensory stimuli are known to improve the walking abilities in PD patients to a considerable extent. Martin [1] was apparently the first to report positive effects of stationary visual cues, such as transverse lines, on gait in PD patients. The utility of visual markers in gait control by PD patients has been further described by several investigators [2–5]. Azulay et al. [6] suggested that gait improvement is facilitated by the perception of motion generated by moving visual cues. However, visual markers cannot be placed along each path the patient takes. Prothero [7] reported beneficial effects on gait in two PD patients using visual cues displayed by a portable head-mounted device. The images were either stationary or in constant perpetual motion, unrelated to the patient's own dynamics (the patient sees the same monotonous cue whether he stands or walks, looking up or down). Baram [8] analyzed the closed-loop effects of real-world visual cues on the regulation and stabilization of gait. In this work we show that such effects must be included in a display of virtual cues in order to achieve significant improvement in the walking abilities of PD patients. We have developed an apparatus which, in contrast to the one reported in [7], detects the patient's body motions and incorporates them in the display, creating, through biofeedback, a closed-loop system. The resulting virtual tiled floor provides the patient with the same visual effects as a real tiled floor.

The Device

The device comprises a head-mounted 3-axis rotational accelerometer, a body-mounted 3-axis translational accelerometer and a see-through head-mounted display, all connected to a wearable computer. It can be operated in two modes: the open-loop mode, in which the virtual tiled floor performs perpetual motion towards the observer at a constant speed, unrelated to the patient's motion or lack thereof, as in [7], and the adaptive closed-loop mode, in which the virtual floor appears to be fixed in space, as a real floor. In both cases, the virtual floor is super-imposed on the real world, seen through the display. In contrast to the open-loop system, depicted in Figure 1(a), the closed-loop system, depicted in Figure 1(b), modifies the image of the virtual tiled floor produced by the image generator, in accordance with the patient's motions, measured by head and body mounted accelerometers. An adaptive filter, depicted in Figure 1(c), learns the patient's tremor dynamics and eliminates them from the signals produced by the accelerometers. For this purpose, we employ the adaptive noise canceler proposed by Widrow and Winter [14]. In our setting, the forward acceleration signal, s , measured along one axis of the body-mounted accelerometer, is corrupted by noise, n , which is correlated with the vertical

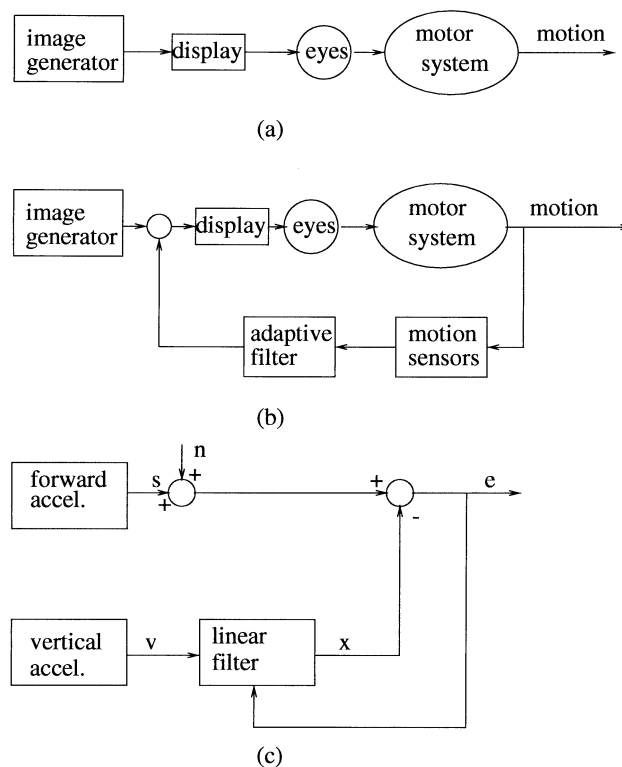


Figure 1. (a) Open-loop system, (b) Closed-loop system, (c) Adaptive tremor filter.

acceleration, v , measured along another axis of the accelerometer, as both noise components are generated by patient tremor. An estimate of s is needed in order to move the virtual tiled floor in accordance with the patient's forward motion. The linear filter has the form $x(i) = \sum_{k=1}^K \alpha_k v(i-k)$, where i is the sampling time index, α_k , $k=1, \dots, K$, are the parameters to be adjusted and K is the filter's 'window' size. A value of $K=5$ was found to produce the best results. Minimizing the expected square of the output, $E\{e^2\}$, with respect to the parameters, employing the LMS algorithm [14], yields $\hat{s} = e$ as an estimate of the forward acceleration. Similar filtering mechanisms are applied to the other accelerometer channels: the turning motion channel and the head tilt channel, in particular.

Medical Tests

Fourteen PD patients of mean age 68.2 ± 8.17 participated in the study. Mean disease duration was 9.36 ± 6.64 and mean clinical severity according to Hoehn and Yahr [9] staging (HY) was 3.04 ± 0.84 . All patient had visual acuity 6/6 with correction when necessary. All tests were performed at the Movement Disorders Clinic, Rambam medical Center, Haifa, Israel, around the same time in the morning, following 12 hours off medications. Before starting a test, each patient was made familiar with the device. Each test consisted of the patient walking a straight track of 10 meters four times. At the start of each test, the patient was verbally instructed to start walking. The time to complete the track and the number of steps for each path were recorded. In the first test (the *reference test*) the display was turned off. In the second test, the open-loop system was turned on, displaying a virtual tiled floor in perpetual motion towards the observer at the maximal speed level which was still comfortable for the patient. The third test employed the adaptive closed-loop system. The order of the second and the third tests was then reversed and the results for each of the tests were averaged, in order to eliminate the effect of training from the comparison. The patients wore the device even when the display was turned off, so as to eliminate the burdening effect of the device from the comparison.

The test results are given in Table 1, where the last four columns show the percentage changes in the performance parameters obtained for the open-loop and the closed-loop systems with respect to the reference test. It can be seen that, in all patients but one, performance was improved (higher speed, longer stride) significantly with respect to the reference test, when the closed-loop system was turned on. This measured improvement also represents the observed improvement in the quality of the steps. Patients who dragged their feet on the ground in the reference test raised them noticeably higher when the closed-loop system was turned on. The one patient who was not helped by the display at all, MR, had no walking impairment (as can be seen from his test parameters, he had, by far, the best performance of all patients in the reference test). The last two rows in the table show the average performance of our patient group (excluding MR, who, as noted before, had no walking impairment). It can be seen that, on average, the proposed closed-loop system improves performance

Table 1. Patient performance results (speed is in meters/second, stride length is in meters)

Patient	Display off			Open-loop system			Closed-loop system			Open-loop improvement			closed-loop improvement		
	Age	yd	HY	Speed	Stride length	Speed	Stride length	Speed	Stride length	Speed %	Stride length %	Speed %	Stride length %	Speed %	Stride length %
YT	74	4	2	0.884	0.465	1.063	0.541	1.107	0.571	20.2	16.3	25.3	22.9	25.3	22.9
ST	72	2	2	0.637	0.339	0.738	0.370	0.772	0.385	15.9	9.1	21.2	13.5	21.2	13.5
JL	77	1	2	0.845	0.435	1.056	0.556	1.272	0.667	25.0	27.8	50.5	53.3	50.5	53.3
MM	67	20	3	0.416	0.256	0.575	0.417	0.535	0.392	38.2	62.9	28.5	52.9	28.5	52.9
BK	61	2	2.5	0.784	0.541	0.918	0.556	0.855	0.588	17.1	2.8	9.1	8.8	9.1	8.8
JS	66	15	4	0.314	0.168	0.073	0.111	0.339	0.220	-76.9	-33.9	8.0	30.7	8.0	30.7
SM	61	15	3	0.686	0.323	0.887	0.400	0.820	0.408	29.3	24.0	19.5	26.5	19.5	26.5
MF	76	5	4	0.774	0.388	1.144	0.488	0.907	0.426	47.8	25.6	17.2	9.6	17.2	9.6
YN	73	11	3	0.695	0.408	0.881	0.444	0.791	0.417	26.8	8.9	13.8	2.1	13.8	2.1
ES	57	3	2	0.620	0.385	0.907	0.500	0.887	0.488	46.2	30.0	43.0	26.8	43.0	26.8
MR	73	10	3	1.038	0.555	0.855	0.476	0.888	0.500	-17.6	-14.2	-14.5	-9.9	-14.5	-9.9
AR	82	20	4	0.508	0.339	0.601	0.400	0.590	0.385	18.3	18.0	16.0	13.5	16.0	13.5
JJ	59	10	4	0.773	0.435	0.864	0.488	0.895	0.488	11.8	12.2	15.9	12.2	15.9	12.2
NM	57	13	4	0.403	0.154	0.243	0.140	0.668	0.351	-39.8	-9.1	65.5	128	65.5	128
mean	68.21	9.36	3.04	0.642	0.357	0.765	0.434	0.803	0.445	13.8	15.0	25.7	30.8	25.7	30.8
std	8.17	6.64	0.84	0.181	0.112	0.318	0.145	0.241	0.116	34.8	22.4	17.2	33.2	17.2	33.2

by about 26% (speed) or 31% (stride length) with respect to the reference test. It should also be noted that the standard deviations of these results are rather high, which implies that the results should be evaluated mainly on an individual basis. Certain Parkinson patients would be helped by the proposed approach to a very significant degree (50%–100%), others would be helped to a lesser degree. Few, in particular those with no walking impairment, would not be helped at all. The average results for the open-loop system are about half as good as those for the closed-loop system. Furthermore, the standard deviations for the open-loop system with respect to the means are drastically higher than those for the closed-loop system and for the reference state. This means that the open-loop system affects different patients in a drastically different way (indeed, for some of the patients the open-loop system gave slightly better results than the closed-loop one). The behaviors of JS and NM are particularly noteworthy in this respect. Both these patients were severely Brady-kinetic, unable to stand or start walking on their own. When the closed-loop display was turned on, both these patients were able to initiate and sustain a near-normal unaided walk. When the open-loop system (perpetual motion display) was turned on, both patients were able to initiate a walk, but then experienced freezing episodes. It can be seen that, for both patients, the performance parameters for the open-loop system are drastically lower than those for the closed-loop system and even those for the reference test. Some patients reported discomfort, dizziness and nausea caused by the perpetual floor motion of the open-loop system. Most patients reported relative comfort with the self-activated, closed-loop adaptive system and indicated a clear preference for it over the open-loop system.

Discussion

Visual cues, long known to affect gait patterns, provide a channel for non-pharmacological therapeutic intervention in PD. In the present study we have demonstrated that it is possible to use virtual reality cues, superimposed on the real world, to help PD patients control their gait. In particular, we have shown that the best effect can be achieved using a closed-loop display which responds to the patient's own motion. Specifically, our device displays a virtual tiled floor, which, as a real floor, appears to be fixed in space, moving with respect to the observer only when he does. In contrast, we have found that an open-loop, non-adaptive cue display causes adverse effects such as dizziness, nausea or even freezing. The mechanism by which visual cues influence gait is still not fully understood. Predictive sensory cues, such as serial transverse lines, may trigger step transitions during walk [2]. Furthermore, transverse lines may help a PD patient scale his stride length, which is abnormally short otherwise, possibly due to underestimated muscle activity required to produce sufficient movement [11]. We suggest that our closed-loop virtual display system produces the same effects as a real tiled floor. We further suggest that the failure of the open-loop virtual display system to produce satisfactory gait control in most patients is caused by the perpetual motion of the image, which, being unaffected by the

patient, is eventually neglected. If, on the other hand, the patient attempts to keep his attention on the perpetual floor motion, his optokinetic system gets continuously stimulated, causing dizziness. In addition, the perpetual floor motion in the open-loop system does not forgive the patient for deviating from the set speed, giving him a sense of confusion and being 'out of sync'. In contrast, the patient using the close-loop system has, by his own body motion, full control of the relative motion of the virtual floor, which, by bio-feedback, helps him regulate his gait. Recently, Hanakawa et al. [12] explored the functional neuroanatomy which underlines visual guided gait in PD patients. They found that the right lateral pre-motor cortex, which is mainly regulated by cerebellar inputs, was activated to a greater extent in PD patients than in age matched healthy individuals by visual transverse lines. On the other hand, the healthy individuals activated mainly the supplementary motor area (SMA), which was under-activated in PD patients. It appears, then, that visually enhanced gait employs different brain pathways in PD patients compared to healthy individuals, bypassing the impaired SMA function. The proposed augmented reality apparatus may serve as a mechanism for activating this alternative pathway. Our study reveals that the gait parameters which are most sensitive to anti-Parkinson medication [13] and are improved by pallidotomy (brain surgery) [14], namely, walking speed and stride length, can also be manipulated, to a similar extent and without some adverse effects, by a closed-loop display of virtual visual cues. The full extent of this approach within a comprehensive diagnosis and care program for movement disorder patients is presently investigated.

References

1. Martin, J. P.: Locomotion and the basal ganglia. In: J. P. Martin (ed.), *The Basal Ganglia and Posture*, London: Pitman medical pp. 20–35, 1967.
2. Morris, M. E., Ianssek, R., Matyas, T. A. and Summers, J. J.: The pathogenesis of gait hypokinesia in Parkinson's disease. *Brain* **117** (1994), 1160–1181.
3. Morris, M. E., Ianssek, R., Matyas, T. A. and Summers, J. J.: The ability to modulate walking cadence remains intact in Parkinson's disease. *Journal of Neurology, Neurosurgery and Psychiatry* **57** (1994), 1532–1534.
4. Bagley, S., Kelly, B., Tunnicliffe, N., et al.: The effect of visual cues on the gait of independently mobile Parkinson's disease patients. *Physiotherapy* **77** (1991), 415–420.
5. Dunne, J. W., Hankey, G. J. and Edis, R. H.: Parkinsonism: upturned walking stick as an aid to locomotion. *Arch. Phys. Med. Rehabil.* **68** (1987), 380–381.
6. Azulay, J. P., Mesure, S., Amblard, B., Blin, O., Sangla, I. and Pouget, J.: Visual control of locomotion in Parkinson's disease. *Brain* 1999 Jan;122 (Pt 1):111–20.
7. Prothero, J. D.: The treatment of akinesia using virtual images. M.Sc. thesis, U. of Washington, 1993.
8. Baram, Y.: Walking on tiles. *Neural. Proc. Lett.* **10** (1999), 81.
9. Hoehn, M. M. and Yahr, M. D.: Parkinsonism: onset, progression and mortality. *Neurology* **17** (1967), 427–42.
10. Beradelli, A., Dick, J. P. and Rothwell, J. C., et al.: Scaling of the size of the first agonist EMG burst during rapid wrist movements in patients with Parkinson's disease. *J. Neurol. Neurosurg. Neuropsychiatry* **49** (1986), 1273–1279.

11. Hanakawa, T., Fukuyama, H., Katsumi, Y., Honda, M. and Shibasaki, H.: Enhanced lateral premotor activity during paradoxical gait in patients with Parkinson's disease. *Ann. Neurol.* **45** (1999), 329–336.
12. Pedersen, S. W., Eriksson, T. and Oberg, B.: Effects of withdrawal of antiparkinson medication on gait and clinical score in the Parkinson patient. *Acta. Neurol. Scand.*, 1991 Jul;84(1):7–13 Siegel KL.
13. Siegel, K. L. and Metman, L. V.: Effects of bilateral posteroventral pallidotomy on gait in subjects with Parkinson's disease. *Arch. Neurol.* **57** (2000), 198.
14. Widrow, B. and Winter, R.: Neural Nets for Adaptive Filtering and Adaptive Pattern Recognition. *Computer* **21** (1988), part 3, 25.