RIC

ARTÍCULO ORIGINAL

Evidence-based design and development of a VR-based treadmill system for gait research and rehabilitation of patients with Parkinson's disease

Alberto Isaac Pérez-Sanpablo,* Arturo González-Mendoza,§ Ivett Quiñones-Uriostegui,* Gerardo Rodríguez-Reyes,† Lidia Núñez-Carrera,* Claudia Hernández–Arenas,‡ Marie Catherine Boll-Woehrlen,|| Aldo Alessi Montero*

* Laboratorio de Análisis de Movimiento Humano, † Laboratorio de Ortesis y Prótesis,
‡ Rehabilitación Neurológica, Instituto Nacional de Rehabilitación.
§ Ingeniería Biomédica, Universidad Iberoamericana.
|| Neurología, Instituto Nacional de Neurología y Neurocirugía.

ABSTRACT

Virtual reality (VR) in neurorehabilitation allows to reduce patient's risk and allows him to learn on a faster way. Up to now VR has been used in patients with Parkinson disease (PD) as a research tool and none of the developed systems are used in clinical practice. The goal of this project is to develop a VR-based system for gait therapy, and gait research of patients with PD designed based on published evidence. The developed system uses a digital camera to measure spatiotemporal gait parameters. The software was developed in C#, using Open-Source libraries that facilitates VR programming. The system has potential uses in clinical and research settings.

Key words. Virtual reality. VR. Virtual environments. Parkinson's disease. PD. Cueing. Treadmill.

Diseño basado en evidencia y desarrollo de un sistema de banda sinfín con RV para investigación y rehabilitación de pacientes con enfermedad de Parkinson

RESUMEN

La realidad virtual (RV) aplicada a la neurorrehabilitación permite reducir el riesgo al que se somete el paciente y le permite a éste aprender una tarea más rápido. A la fecha, la RV se ha utilizado en pacientes con enfermedad de Parkinson (EP) sólo como herramienta de investigación, ya que ninguna de las aplicaciones desarrolladas ha alcanzado el punto de aplicación en la clínica. El objetivo de este proyecto es desarrollar un sistema de RV para investigación y terapia de marcha de pacientes con EP, con diseño basado en la evidencia. El sistema desarrollado utiliza una cámara digital para registrar parámetros espacio-temporales de la marcha del paciente. El software del sistema fue desarrollado en lenguaje C# usando librerías de código abierto que facilitan la programación de VR. El sistema desarrollado tiene utilidad potencial en el ámbito de investigación y la clínica.

Palabras clave. *Realidad virtual. RV. Ambientes virtuales. Enfermedad de Parkinson. EP. Estimulación. Banda sinfín.*

INTRODUCTION

Virtual reality (VR) has been used in the neurorehabilitation field to provide interfaces where patients can interact within virtual worlds that simulates real worlds. VR allows a high level of control of the interaction and the experience provided to the patient within the virtual world.[1] This allows health care professionals to make tasks easier, to reduce the patient's risk, to improve patient's attachment to treatment by making it more entertaining, to provide controlled stimuli to patient, to measure the patient's response, and finally to optimize the effect of therapy by individualization of therapy based on patient condition and progress. It shows the advantages of VR-based therapies compared with traditional procedures.[2]

Motivated also by advantages of technology and reduction of costs, during the last years more VR-based therapies have emerged, some of them based on over-excitement and unrealistic expectations by developers and health care professionals.[1]

Evidence about the efficacy of VR-based therapies should be analyzed carefully. The best evidence in evaluating the efficacy of a therapy is the results of systematic reviews and randomized, controlled clinical trials (RCT). However, up to now there is no systematic review or RCT about efficacy of VR-based therapies for Gait rehabilitation of patients with Parkinson's disease (PD).

VR has been used in PD patients to study cognitive deficits,[3,4] sleep dysfuntions,[5] perception dysfuntions,[6,7] motor learning,[8,9] postural control[10,11] and gait,[2,12] but the only published RCT studies the effect of a VR-based therapy just on postural control[11] and not on gait.

Patients with PD suffer from a progressive disabling disorder, which is mainly due to the involvement of the basal ganglia.[13] Characteristic symptoms of the disease are tremor, rigidity, postural instability, loss of speed or limiting the extent of movement (hypokinesia) and inability to perform voluntary movements (akinesia).[14] Hypokinesia is one of the major motor limitations and determines the disability and quality of life of these people.[15]

Most of the previous VR-based systems developed to study PD dysfunctions are research systems and none of them have reached the application stage during clinical practice.[1,2] One reason is that systems are too complex and too expensive for common clinical practice due to its high power. This capability allows users to study a wide range of neurological conditions; however, these systems are too complex for clinical practice. The design of those systems should be based both on a human centered approach[1] and on the best published evidence.

Therefore the aim of this work is to design and implement a VR-based system for gait therapy and gait research for patients with PD based on published evidence and on human centered approach.

MATERIAL AND METHODS

Design philosophy

Philosophy of design was based on Evidence-Based Medicine and on Human centered design for interactive systems like the standard ISO 9241-210:2009.[16] Therefore a clear understanding of task is needed: context of use, user requirements, organization requirements, and appropriate allocation of function. As a result, the present system will be used in gait research and gait therapy as a supplement to conventional pharmacological treatment of ambulatory PD patients within a high specialty public hospital such as the Instituto Nacional de Rehabilitación (INR). Further system design parameters are based on published evidence. A review of the medical and technical literature was conducted in the MEDLINE and XPLORE databases looking for studies about Gait Therapies for PD subjects including the terms external cueing (EC) and treadmill training (TT).

PD subjects

PD subjects intended to use the system should have a Hoehn-Yahr (H&Y) score from 1 to 3, and on stable pharmacological treatment. PD subjects should not have cognitive impairment, uncorrected visual and hearing impairments, or unpredictable large off episodes. That means that PD subjects are able to walk with few or any physical assistance and consequently to be able to walk safely over treadmill. Also they should not have any motor alterations due to medication changes, perceive properly visual and hearing stimulus and finally they must be able to understand and manage virtual environments.

The typical range of walking speed and cadence for the PD subject is 1.3-3.9 km/h and 1.36 to 2.22 steps per second respectively, according to published

Table 1. Characteristics of PD subjects intended to use the system.

Age [years]	20-80
Sex	Male/Female
EP diagnostic	Confirmed by neurologist
Pharmacologic therapy	Stable and controlled
Hoehn & Yahr Scale	1-3
UPDRS 29	2-3
UPDRS 37	0
UPDRS 39	≤ 2
Mini Mental Test	> 23
Average height (SD) [m]	1.55 (0.09)
Average gait velocity (SD) [m/s]	0.83 (0.19)
Mean cadence (max) [steps/min]	105.3 (122)
Step length (min) [cm]	47.7 (22)

UPDRS: Unified Parkinson's disease rating scale. SD: standard deviation. Min: minimum. Max: maximum.

results[13] and previous experiments performed by the group at the INR.[49] Complete characteristics for PD subjects are shown on table 1.

Gait therapies

There are more than 50 studies and one systematic review found in the literature[17] about EC in PD subjects. It can be seen that visual, auditory, proprioceptive, attentional, tactile, vibrational and kinesthetic cues are used to improve gait of PD subjects. However most of studies have a lack of methodological quality because do not describe properly the intervention. Also there are more than 103 studies and 12 reviews[2,13,15,18-26] about TT in patients with PD. It is concluded that TT improves gait velocity and step length in patients from 1 to 3 stages of H&Y scale immediately after training.[13] However it is concluded that further research is needed before using this therapy in clinical practice due to methodological differences between studies such as training design, velocity, intensity and duration of therapy.

Outcomes measures

Differences between gait therapy studies are also shown in outcomes measures. Outcome measures include clinical outcomes and functional ones measured either by subjective or objective ways. In order to identify essential functional outcomes within a gait therapy intervention for PD subjects, health care professionals were consulted and selected publications from previous search about EC[17] and TT[2,13,15,18-26] were reviewed.

For this research, gait velocity, cadence, step length and step time variability (STV) were selected as functional outcomes.

Model for gait therapy of PD subjects

A simple model of gait for therapy is proposed according to identified essential functional outcomes measures of gait. Gait consists of three fundamental spatiotemporal parameters: walking speed, cadence and step length. Parameters are related as follows:

$$\text{walking speed} = \text{cadence} * \text{step length}$$

EC and TT interventions are intended to give control over spatiotemporal parameters. Step length has been controlled mainly by using visual stimuli.[27-38] More effective visual stimuli are transverse lines placed over the floor[28,30] with 50 cm length and 5 cm width[30] and separated at a distance equal to the ideal step length for the subject based on his height, age and gender.[27,32,33,36] Auditory stimuli have been used to control cadence.[31,35,37,39-45] Auditory stimuli are high frequency beats of 40 ms duration produced by headphones[39,42] at the same frequency of subject's cadence,[35,41,44] or from10 to 20% bigger for PD subjects who do not suffer freezing of gait.[31] Treadmill has the function of controlling the walk-ing speed. Treadmill training has been used in combination with other therapy modalities like body weight support (BWS), however it has been found that positive effect of treadmill training is independent of BWS.[46-48] Training treadmill velocity equal to speed of PD subject on over ground walking is preferred due to the fact that it allows more PD subjects who are not in a high fitness state to benefit from this therapy,[49] and avoids fatigue issues for gait research and it has the same effect than training at maximum tolerated walking speed.[46,50]

Safety issues

The main safety concerns about VR-based systems are motion sickness and degraded limb and postural control. However recent similar studies have not found any of them.[9,12] Furthermore motion sickness is not expected since a mismatch between the optical flow perceive by the subject and his movement is either expected. Additionally, changes in walking speed for gait therapy and gait research in patients with PD are seldom and minor.[13]

System validation

Bench tests and performance tests were done to validate the system. Bench tests were made to test the performance of the software used to calculate gait related parameters. Simultaneous measures of on-floor gait of 2 healthy volunteers were done using the software developed to calculate gait parameters and the commercial GaitRite system (CIR Systems Inc., Clifton, USA) which is the gold standard for this kind of measures. Measures were taken along a 3 m flat surface corresponding to GaitRite sensing area. Camera used by the software for calculation of gait parameters was placed next to the GaitRite system at a distance enough to ensure a complete sagittal view of the GaitRite sensing area. The subjects' step length measures were compared between both systems and the percentage error was calculated as a measure of software performance on calculation of gait parameters.

Performance tests were made to test whole system performance on 5 healthy volunteers during a complete 20 min gait therapy session. Simultaneous measures of gait related parameters of all subjects walking on a treadmill were performed using an instrumented treadmill GaitTrainer II (Biodex, Shirley, USA) and the developed system during 6 min at 3 different treadmill velocities: 1.5 km/h, 2.5 km/h and 3.5 km/h. Treadmill speed was increased on a period of time of 1 min. Subjects' step length, cadence and gait velocity were compared and the percentage error for each measurement was calculated as a measure of system's performance.

OBJECTIVES

Therefore we focused on the design and implementation of a VR-based system for gait research and gait rehabilitation for PD subjects with a H&Y score from 1 to 3, who are able to walk with few or any physical assistance, and do not have any cognitive impairment, uncorrected visual and hearing impairments, or unpredictable or large off episodes. This system should allow the control over walking speed, cadence and step length by means of treadmill, auditory stimuli and visual stimuli respectively. Visual stimuli are delivered through a virtual environment with transverse lines placed over the floor of the virtual environment with 50 cm length and 5 cm width and separated a distance equal to the ideal step length for each subject based on his height, age and gender. Visual stimulus is accompanied by an auditory stimulus consisting of high frequency beats of 40 ms duration produced by headphones at the same frequency of subject's cadence. Treadmill velocity is set equal to over ground walking speed of PD subject. This system aims to measure gait velocity, cadence, step length and STV parameters through image processing techniques in real time. All PD subjects wear for safety, a body support harness secured to an overhead system.

RESULTS

Technical requirements

The main requirements of the system are both accurate detection of steps over treadmill by image processing techniques and deployment of visual and auditory stimuli in time with a latency of the feedback lower than 50 ms.[9]

System was built up according to previously mentioned design parameters based on published evidence. Whole system description is as follows.

Hardware and spatial configuration of the system

The treadmill's lower speed used by the system was around 1.5 km/h. This feature is essential to allow PD subjects to use the system. Camera used for image acquisition was placed at the side of the treadmill. The system used a camera with a sampling rate at least of 22 frames per second (fps). This characte-

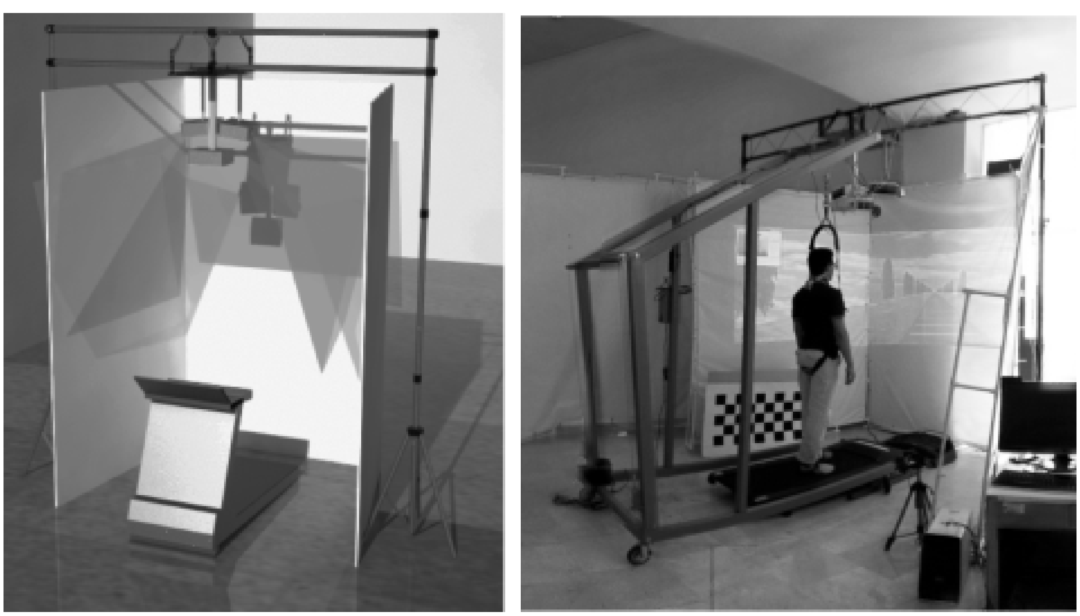

Figure 1. Concept design and picture of the developed system.

ristic is essential to guarantee the step detection with an error around 10 percent when PD subject is walking at 2.22 steps per second. Theoretically maximum time error in step detection could be 45 ms.

Previously mentioned visual stimuli are delivered through a virtual environment. To display the virtual environment the system uses three screen displays. The first screen has a size of 2 x 2.60 m and is in between other two screens of the same size. Screens guarantee complete subject's immersion in the virtual environment when he is walking over a typical treadmill of 160 cm long positioned at 1 m distance to frontal screen.[49] For safety of the patient the system comprises a partial body weight support, designed at the INR, for avoiding the camera occlusion. Conceptual design and spatial configuration of the system is shown in figure 1.

Virtual environment is displayed with three short throw projectors model MX810ST (Benq, Taipei, Taiwan) with a throw distance value of 0.6 m, and a display update rate of 60 Hz. Projectors are positioned to a distance around 160 cm away from the screens and 273 cm above the level of the floor. The computer has an Intel core i7 processor, 16 Gb Ram memory, and a ATI HD 5970 1Gb graphic card, that supports up to three monitors and real time rendering.

Software

The software was programmed in C# language for Windows 7. This programming language was chosen because it has the libraries to control low-level hardware such as webcams, and graphics cards for the development of virtual environments, and also has free tools that facilitate the game programm-ing called Microsoft XNA (Microsoft, Redmond, WA, USA). The system software displays the virtual environment, and also deploys the visual and auditory stimuli; such stimuli are displayed depending on the detection of events like heel strike and speed. The program uses threads to ensure a good performance of the system. There are three main actions running in threads:

- Image acquisition and marker detection.
- Calculation of walking parameters (step length, cadence and gait velocity).
- Display of the VR interface.

Image acquisition and image processing is performed using the library touchless (Microsoft, Redmond, WA, USA), which is an open source library; this library allows video flow stream and detection of color markers. Markers are detected and segmented

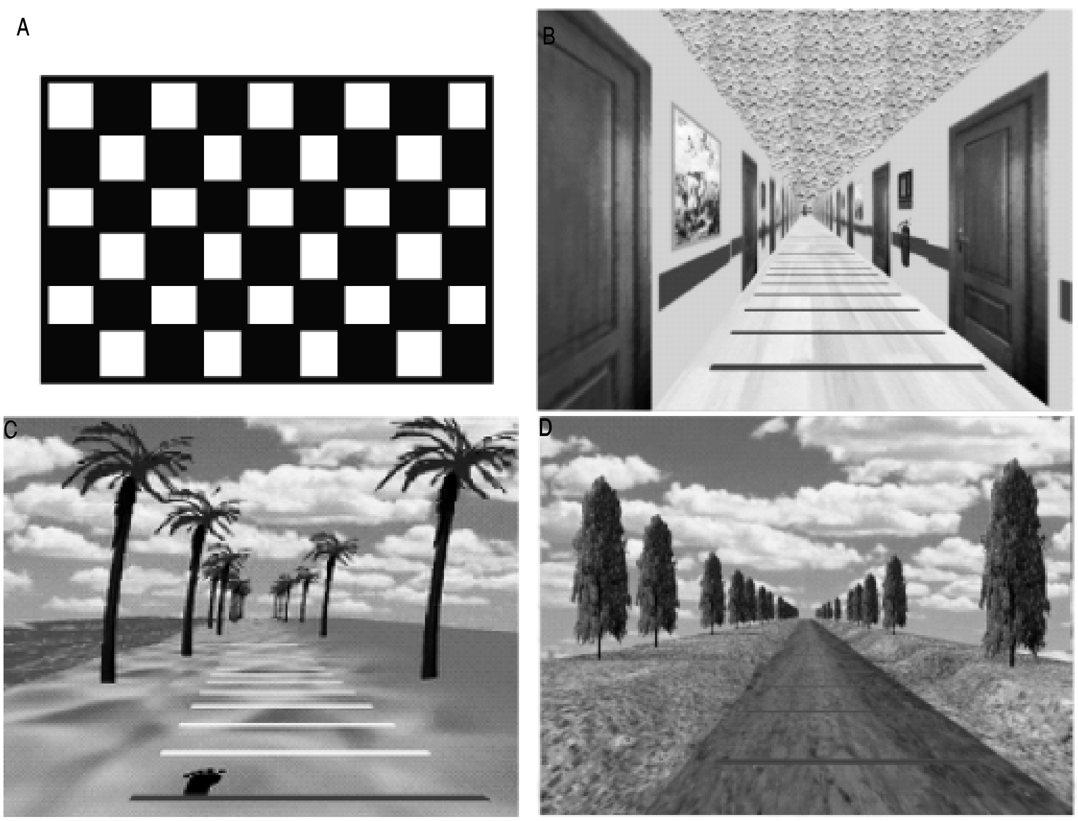

*Figure 2. **A.** Camera calibration grid. B. Indoor virtual environment showing transverse lines used as visual stimuli. C. Beach like outdoor virtual environment showing the current step line highligh-ted on green color with a feedback footprint above the line meaning that last step was larger than required step. D. Forest like outdoor virtual environment.*

in Hue-Saturation-Lightness (HSL) color space. Subject's feet are detected using two color markers.[51] Each foot has a different color. In order to obtain spatial coordinates of markers, the camera calibration is carried out using a rectangular grid, as shown in figure 2A.

Gait velocity, cadence, and step length parameters are calculated based on identification of gait events like heel strike and toe off. Gait events are detected based on local minima and maxima of feet coordinates: local minimum coordinates along time indicate heel strike i.e. cadence is calculated as the number of heel strikes in a minute. Step length is calculated as the spatial difference between the local minimum of the first foot and the next maximum of the contralateral foot. Walking speed in meters per second is calculated every minute using both feet average step length in centimeters (SL) and number of steps (NS):

$$\text{Walking speed} = \frac{\overline{SL} * NS * 60}{100,000}$$

Once acquired these parameters the software sends the visual and auditory stimuli to the patient through the VR interface.

Virtual environment

The virtual environment (VE) was developed in Softimage, this program developed by Autodesk is free license for non-commercial projects, and facilitates the development of models in 3D and integration to XNA library for games. The system has three VEs, the first one simulates an indoor therapy in a hall way with doors (Figure 2B), the second and third environment simulates outdoor training in a beach and a forest respectively (Figures 2C-2D). The system displays the three VE in an infinite hallway that is made thought the duplication of finite hallways.

System stimuli and feedback

As mentioned above the auditory feedback is 40 ms beats with a frequency of 1,500 kHz. Auditory stimulus is controlled by a timer event. Visual stimulus consists of two elements, a current active step line which is green highlighted and a footprint which shows the length of the previous subject's step. If the last step length is larger than the required step length the footprint will be deployed further the green highlighted line. If last step length is shorter than required step length, footprint will be displayed before the green highlighted line. An example is shown in figure 2C.

System database

The database is an internal control that manages patients list and studies list. Information is stored in an excel spreadsheet to facilitate data manage-

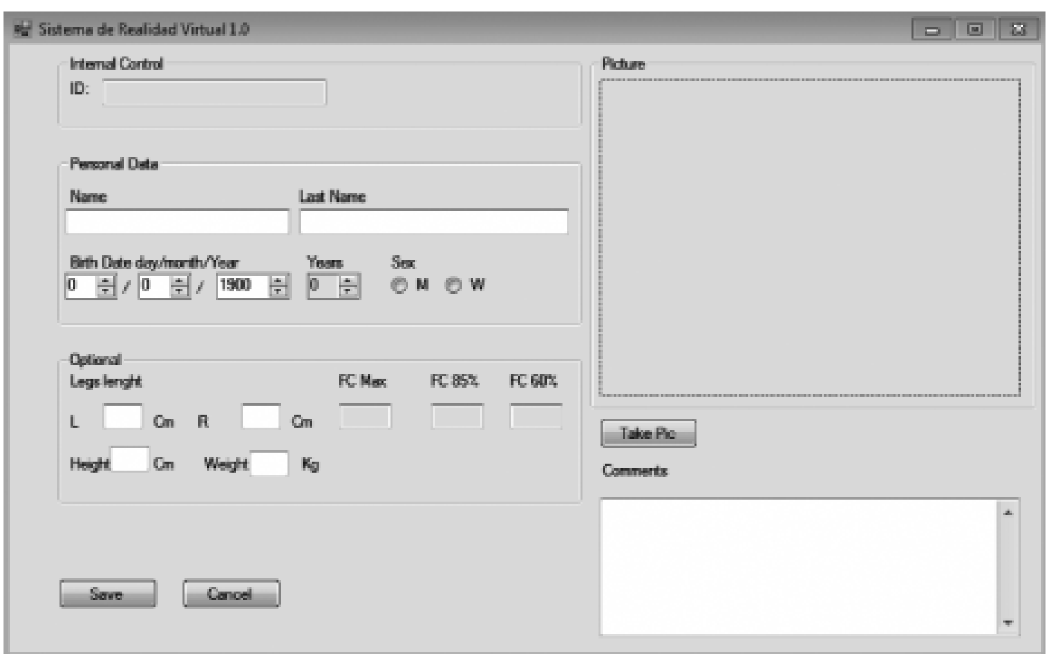

Figure 3. Database entry form of a new patient.

ment. The patient's list keeps information such as name, last name, date of birth, and age for proper identification of the patient. Further optional data as the length of the legs, height, age and maximal heart rate can be saved for further analysis. Also a patient's picture and relevant comments can be saved optionally. The figure 3 shows how the system allows adding a new patient. The data stored in each study are the number of study, patient identification number, date of study, step lengths and a study video.

System validation

It was mentioned before that bench tests were done to compare the results of the algorithm to calculate step length with simultaneous measures of on-floor gait recorded by the GaitRite system. The average percentage error of step length calculation of the 2 healthy volunteers was 2.6% while the maximum percentage error was 6.2%.

As mentioned before, performance tests were done to compare the results of the algorithm with simultaneous measures of treadmill gait recorded by the GaitTrainer II. In total 10,000 steps were recorded during the 20 min of treadmill gait of the 5 healthy volunteers. Average and maximum percentage of error of step length calculation are 4.7% and 6.2% respectively. Average and maximum percentage of error for cadence are 2.1 and 6.1% respectively. Average and maximum percentage of error of gait velocity are 4.9 and 11.4% respectively.

DISCUSSION

VR has a big potential in neurorehabilitation however VR applications should be analyzed carefully. More research is needed to understand both the positive and negative effects of VR interventions.

The first step within this process is system design. Design of the interactive systems should consider human centered issues and also previous published data in order to make meaningful applications that can help to solve clinical and research questions and so, it is possible to accelerate the process of providing a technological product applied into clinical practice.

This requires interdisciplinary teams including professionals of neuro-psychology, technology, medicine and therapists.

The developed system fulfills all the previous requirements. This system is based on evidence coming from published studies and on knowledge of health care professionals, consequently it has the potential to be used not only in research field but also into clinical setting.

ACKNOWLEDGMENT

Authors greet to the Mexican National Council of Science and Technology CONACyT for its support by the protocol number 2010-01-139718.

REFERENCES

1. Riva G. Applications of virtual environments in medicine. *Methods Inf Med* 2003; 42: 524-34.
2. Holden MK. Virtual environments for motor rehabilitation: review. *Cyberpsychol Behav* 2005; 8: 187-219.
3. Albani G, Raspelli S, Carelli L, Morganti F, Weiss PL, Kizony R, Katz N, et al. Executive functions in a virtual world: a study in Parkinson's disease. *Stud Health Technol Inform* 2013; 154: 92-6.
4. Klinger E, Chemin I, Lebreton S, Marie RM. Virtual action planning in Parkinson's disease: a control study. Cyberpsychol Behav 2006; 9: 342-7.
5. Albani G, Raspelli S, Carelli L, Priano L, Pignatti R, Morganti F, Gaggioli A, Weiss PL, Kizony R, Katz N, Mauro A, Riva G. Sleep dysfunctions influence decision making in undemented Parkinson's disease patients: a study in a virtual supermarket. Stud Health Technol Inform 2011; 163: 8-10.
6. Davidsdottir S, Wagenaar R, Young D, Cronin-Golomb A. Impact of optic flow perception and egocentric coordinates on veering in Parkinson's disease. *Brain* 2008; 131: 2882-93.
7. Onofrj M, Bonanni L, Albani G, Mauro A, Bulla D, Thomas A. Visual hallucinations in Parkinson's disease: clues to separate origins. *J Neurol Sci* 2006; 248: 143-50.
8. Messier J, Adamovich S, Jack D, Hening W, Sage J, Poizner H. Visuomotor learning in immersive 3D virtual reality in Parkinson's disease and in aging. *Exp Brain Res* 2007; 179: 457-74.
9. Myall DJ, MacAskill MR, Davidson PR, Anderson TJ, Jones RD. Design of a modular and low-latency virtual-environment platform for applications in motor adaptation research, neurological disorders, and neurorehabilitation. *IEEE Trans Neural Syst Rehabil Eng* 2008; 16: 298-309.
10. Suarez H, Geisinger D, Suarez A, Carrera X, Buzo R, Amorin I. Postural control and sensory perception in patients with Parkinson's disease. *Acta Otolaryngol* 2009; 129: 354-60.
11. Yen CY, Lin KH, Hu MH, Wu RM, Lu TW, Lin CH. Effects of virtual reality-augmented balance training on sensory organization and attentional demand for postural control in people with Parkinson disease: a randomized controlled trial. *Phys Ther* 2011; 91: 862-74.
12. Mirelman A, Maidan I, Herman T, Deutsch JE, Giladi N, Hausdorff JM. 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* 2011; 66: 234-40.
13. Mehrholz J, Friis R, Kugler J, Twork S, Storch A, Pohl M. Treadmill training for patients with Parkinson's disease. *Cochrane Database Syst Rev* 2010; CD007830.
14. Jankovic J. Parkinson's disease: clinical features and diagnosis. *J Neurol Neurosurg Psychiatry* 2008; 79: 368-76.
15. Morris ME. Movement disorders in people with Parkinson disease: a model for physical therapy. *Phys Ther* 2000; 80: 578-97.

16. International Organization for Standardization, ISO 13407 Human-Centered Design for Interactive Systems. International Organization for Standardization 1999.
17. Lim I, van Wegen E, de Goede C, Deutekom M, Nieuwboer A, Willems A, Jones D, et al. Effects of external rhythmical cueing on gait in patients with Parkinson's disease: a systematic review. *Clin Rehabil* 2005; 19: 695-713.
18. de Goede CJ, Keus SH, Kwakkel G, Wagenaar RC. The effects of physical therapy in Parkinson's disease: a research synthesis. *Arch Phys Med Rehabil* 2001; 82: 509-15.
19. Deane KH, Ellis-Hill C, Jones D, Whurr R, Ben-Shlomo Y, Playford ED, Clarke CE. Systematic review of paramedical therapies for Parkinson's disease. *Mov Disord* 2002; 17: 984-91.
20. Goodwin VA, Richards SH, Taylor RS, Taylor AH, Campbell JL. The effectiveness of exercise interventions for people with Parkinson's disease: a systematic review and meta-analysis. *Mov Disord* 2008; 23: 631-40.
21. Keus SH, Munneke M, Nijkrake MJ, Kwakkel G, Bloem BR. Physical therapy in Parkinson's disease: evolution and future challenges. *Mov Disord* 2009; 24: 1-14.
22. Morris ME, Iansek R, Galna B. Gait festination and freezing in Parkinson's disease: pathogenesis and rehabilitation. *Mov Disord* 2008; 23(2): S451-S460.
23. Morris ME, Martin CL, Schenkman ML. Striding Out With Parkinson Disease: Evidence-Based Physical Therapy for Gait Disorders. *Phys Ther* 2010; 90(2): 280-8.
24. Nieuwboer A. Cueing for freezing of gait in patients with Parkinson's disease: a rehabilitation perspective. *Mov Disord* 2008; 23(2): S475-S481.
25. Smidt N, de Vet HC, Bouter LM, Dekker J, Arendzen JH, de Bie RA, Bierma-Zeinstra SM, et al. Effectiveness of exercise therapy: a best-evidence summary of systematic reviews. *Aust J Physiother* 2005; 51: 71-85.
26. Rubinstein TC, Giladi N, Hausdorff JM. The power of cueing to circumvent dopamine deficits: a review of physical therapy treatment of gait disturbances in Parkinson's disease. *Mov Disord* 2002; 17: 1148-60.
27. Iansek R, Huxham F, McGinley J. The sequence effect and gait festination in Parkinson disease: contributors to freezing of gait? *Mov Disord* 2006; 21: 1419-24.
28. Morris ME, Huxham F, McGinley J, Dodd K, Iansek R. The biomechanics and motor control of gait in Parkinson disease. *Clin Biomech* 2001; 16: 459-70.
29. Sidaway B, Anderson J, Danielson G, Martin L, Smith G. Effects of long-term gait training using visual cues in an individual with Parkinson disease. *Phys Ther* 2006; 86: 186-94.
30. Azulay JP, Mesure S, Amblard B, Blin O, Sangla I, Pouget J. Visual control of locomotion in Parkinson's disease. *Brain* 1999; 122(Pt. 1): 111-20.
31. Frazzitta G, Maestri R, Uccellini D, Bertotti G, Abelli P. Rehabilitation treatment of gait in patients with Parkinson's disease with freezing: a comparison between two physical therapy protocols using visual and auditory cues with or without treadmill training. *Mov Disord* 2009; 24: 1139-43.
32. Galletly R Brauer SG. Does the type of concurrent task affect preferred and cued gait in people with Parkinson's disease? *Aust J Physiother* 2005; 51: 175-80.
33. Morris M, Iansek R, McGinley J, Matyas T, Huxham F. Three-dimensional gait biomechanics in Parkinson's disease: evidence for a centrally mediated amplitude regulation disorder. *Mov Disord* 2005; 20: 40-50.
34. Azulay JP, Mesure S, Blin O. Influence of visual cues on gait in Parkinson's disease: contribution to attention or sensory dependence? *J Neurol Sci* 2006; 248: 192-5.
35. Jiang Y Norman KE. Effects of visual and auditory cues on gait initiation in people with Parkinson's disease. *Clin Rehabil* 2006; 20: 36-45.
36. Morris ME, Iansek R, Matyas TA, Summers JJ. Stride length regulation in Parkinson's disease. Normalization strategies and underlying mechanisms. *Brain* 1996; 119(Pt. 2): 551-68.
37. Suteerawattananon M, Morris GS, Etnyre BR, Jankovic J, Protas EJ. Effects of visual and auditory cues on gait in individuals with Parkinson's disease. *J Neurol Sci* 2004; 219: 63-9.
38. van Wegen E, Lim I, de Goede C, Nieuwboer A, Willems A, Jones D, Rochester L, et al. The effects of visual rhythms and optic flow on stride patterns of patients with Parkinson's disease. *Parkinsonism Relat Disord* 2006; 12: 21-7.
39. Nieuwboer A, Baker K, Willems AM, Jones D, Spildooren J, Lim I, Kwakkel G, et al. The short-term effects of different cueing modalities on turn speed in people with Parkinson's disease. *Neurorehabil Neural Repair* 2009; 23: 831-6.
40. del Olmo MF, Cudeiro J. Temporal variability of gait in Parkinson disease: effects of a rehabilitation programme based on rhythmic sound cues. *Parkinsonism Relat Disord* 2005; 11: 25-33.
41. Ledger S, Galvin R, Lynch D, Stokes EK. A randomised controlled trial evaluating the effect of an individual auditory cueing device on freezing and gait speed in people with Parkinson's disease. *BMC Neurol* 2008; 8: 2008.
42. Rochester L, Nieuwboer A, Baker K, Hetherington V, Willems AM, Chavret F, Kwakkel G, et al. The attentional cost of external rhythmical cues and their impact on gait in Parkinson's disease: effect of cue modality and task complexity. *J Neural Transm* 2007; 114: 1243-8.
43. Satoh M, Kuzuhara S. Training in mental singing while walking improves gait disturbance in Parkinson's disease patients. *Eur Neurol* 2008; 60: 237-43.
44. Willems AM, Nieuwboer A, Chavret F, Desloovere K, Dom R, Rochester L, Kwakkel G, et al. Turning in Parkinson's disease patients and controls: the effect of auditory cues. *Mov Disord* 2007; 22: 1871-8.
45. Cho C, Kunin M, Kudo K, Osaki Y, Olanow CW, Cohen B, Raphan T. Frequency-velocity mismatch: a fundamental abnormality in parkinsonian gait. *J Neurophysiol* 2010; 103: 1478-89.
46. Cakit BD, Saracoglu M, Genc H, Erdem HR, Inan L. The effects of incremental speed-dependent treadmill training on postural instability and fear of falling in Parkinson's disease. Clin Rehabil 2007; 21: 698-705.
47. Protas EJ, Mitchell K, Williams A, Qureshy H, Caroline K, Lai EC. Gait and step training to reduce falls in Parkinson's disease. NeuroRehabilitation 2005; 20: 183-90.
48. Bello O, Sanchez JA, Fernandez-del-Olmo M. Treadmill walking in Parkinson's disease patients: adaptation and generalization effect. *Mov Disord* 2008; 23: 1243-9.
49. Perez-Sanpablo AI, Zamora-Contreras MD, Hernandez-Arenas C, Quiñones-Uriostegui I, Rodriguez-Reyes G, Nuñez-Carrera L. Familiarization to Treadmill Walking in Unimpaired Parkinson's Disease Patients. en ISB2011. International Society of Biomechanics 2011. Bruselas, Bélgica.
50. Pohl M, Rockstroh G, Ruckriem S, Mrass G, Mehrholz J. Immediate effects of speed-dependent treadmill training on gait parameters in early Parkinson's disease. *Arch Phys Med Rehabil* 2003; 84: 1760-6.
51. Fellin WCRRE, Royer TD, Davis IS. Comparison of methods for Kinematic identification of footstrike and toe-off during overground and tradmill running. *J Science and Medicine in Sport* 2010; 13: 646-50.

Reimpresos:

Alberto Isaac Pérez-Sanpablo
Torre de Investigación, Piso 7
Instituto Nacional de Rehabilitación
Av. México-Xochimilco, Núm. 289
Col. Arenal de Guadalupe
14389, México D.F.
Tel.: 5999-1000, Ext. 19801
Correo electrónico: aisaacmx@gmail.com

Recibido el 20 de febrero 2013.
Aceptado el 20 de septiembre 2013.