31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

Dynamic Control of a Moving Platform using the CAREN System to Optimize Walking inVirtual Reality Environments

Hassan El Makssoud, Carol L. Richards, and François Comeau

***Abstract*—Virtual reality (VR) technology offers the opportunity to expose patients to complex physical environments without physical danger and thus provides a wide range of opportunities for locomotor training or the study of human postural and walking behavior. A VR–based locomotor training system has been developed for gait rehabilitation post-stroke. A clinical study has shown that persons after stroke are able to adapt and benefit from this novel system wherein they walk into virtual environments (VEs) on a self-paced treadmill mounted on a platform with 6 degrees of freedom. This platform is programmed to mimic changes in the terrain encountered in the VEs. While engaging in these VEs, excessive trunk movements and speed alterations have been observed, especially during the pitch perturbations accompanying uphill or downhill terrain changes. An in-depth study of the subject`s behavior in relation to the platform movements revealed that the platform rotational axes need to be modified, as previously shown by Barton et al [2], and in addition did not consider the subject`s position on the treadmill. The aim of this study was to determine an optimal solution to simulate walking in real life when engaging in VEs.**

I. Introduction

Intensive practice of goal-oriented locomotor tasks in a safe and varied environment promotes the re-acquisition of walking skills in persons recovering from a stroke [5]. Virtual environments (VEs) have great potential as test beds for gait re-training by providing safe, controlled environments that can expose patients to varied physical and mental challenges. A Virtual reality (VR)–based locomotor training system has been developed for gait rehabilitation post-stroke [3, 4]. The locomotor system consists of a self-paced treadmill mounted on a Stewart platform [7] (Rexroth Bosch group - Hydraulic 6 degrees of freedom (DOF) Micro motion system). The treadmill itself is embedded in a 2m circular top surface on the platform and fits flush with the surrounding floor of the room. VEs that are synchronized with the speed of the treadmill and the motions of the platform are rear-projected onto a screen in front of the walking subject. This system is controlled by the CAREN software (Computer Assisted Rehabilitation Environments, Motek Amsterdam) which consists of several processes and applications distributed on multiple computers (figure 1). In addition, sensors are placed on the subject's trunk (upper thorax), sacrum and the right and left legs to record the movements of body segments with the Fastrak Polhemus system (a 3D electromagnetic system for motion tracking).

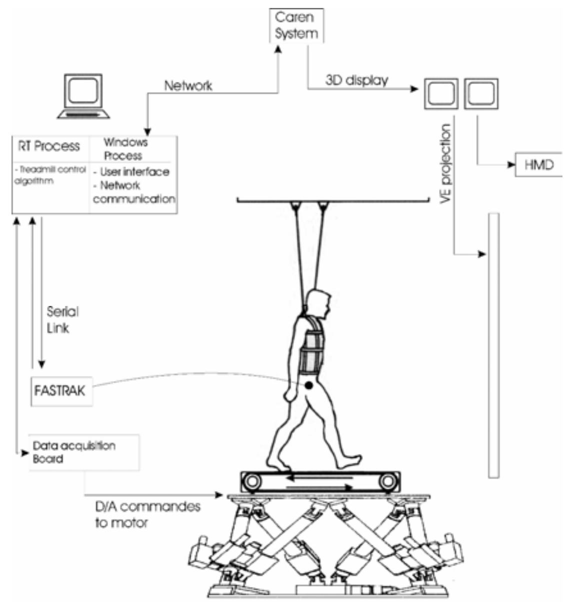

Fig. 1. Schematic of the locomotor system; the subject walks on a self-paced treadmill mounted on a 6 DOF motion platform into a VE projected onto a large screen [5].

A study was conducted to test the capability of persons recovering from a stroke to be trained with the system. This study demonstrated that patients are able to adapt to this novel VR system and be immersed in the VEs for gait training [4]. An in-depth analysis of the movements of the subject when walking on the treadmill, however, revealed excessive translational movements and speed perturbations related to the platform rotations (see non-corrected movements in figures 5 and 6 which illustrate the anterior-posterior (a/p) displacements in the progression plane and the speed of a subject walking on the treadmill in a VE scene where pitch rotations of the platform are produced). These observations led to the identification and correction of two sources of perturbation: 1) the uncorrected default axes of rotation of the Stewart mechanism for our set-up, and 2) the centre of rotation (CoR) of the platform is not in the optimal

C.L. Richards is a Professor in the Department of Rehabilitation, Faculty of Medicine, Laval University and Director of the Centre for Interdisciplinary Research in Rehabilitation and Social Integration (CIRRIS), 525 boulevard Hamel, Québec G1M2S8 Canada. (e-mail: carol.richards@rea.ulaval.ca).

H. El Makssoud is a postdoctoral fellow (Laval University) of the CIHR Multidisciplinary Team in Locomotor Rehabilitation (e-mail: Hassan.Makssoud@cirris.ulaval.ca).

position for a walking subject. Incorrect movements of the platform affect the simulation of the movements experienced by the subject walking in the VEs. The objective of the present study is twofold: 1) to establish a correction method for controlling the platform to reproduce real life sensations when walking in the VEs and 2) to describe the evaluation of this method.

II. METHOD

A. Characterization and Correction of the Moving Platform System

The functionality of the movable platform used in the locomotor training system allows moving in six DOF with movement characteristics such as excursion limits and velocities, comparable to any moveable platform reported in the posture and balance literature [1]. Moreover, it can support a top surface 2m in diameter thus providing a relatively large surface for stepping, or other activities, as well as the installation of a treadmill or other devices onto the surface. We embedded a self-paced treadmill which offers a moving carpet surface of 0.6m wide by 1.5m long and is fixed on the platform surface [4, 6]. This structure moves the surface of the treadmill 36 cm above the original base surface of the Stewart platform. Thus undesirable translations are produced at the treadmill level even though pure roll and pitch movements are sent to the platform controller.

A method of identifying the platform's default axes of rotation and a mathematical method to relocate its axes of rotation is now available [2]. This approach consists of fixing two reference lines that intersect at the center of the top surface of the platform (figure 2A). We then found a vector perpendicular to the surface of the platform located at this center (Figure 2B). To find the default axes of rotation, the platform is then successively rotated and the distances between the intersections of the perpendicular lines are minimised (figure 2B). At the minimum position the mean of the coordinate values of the intersections over successive positions represents the axis of rotation for each plane and its standard deviation the error associated with this estimation. To implement this procedure, two Optotrak markers (infra-red emitting diodes) are placed on each reference line to define the X (P_1-P_2) and Z (P_3-P_4) axes (figure 2A), while Y is the vertical projected axis. Two processes were used to identify the position of the default axes: the pitch axis using P_1-P_2 in the XY plane (sagittal plane), and the roll axis using P_3-P_4 in the YZ plane (frontal plane). The results of the identified Default axes of the Stewart Platform (DaSP) for pitch and roll rotation movements are given in table 1.

The rotation of the platform around a New axis at the Treadmill Surface (NaTS) can be achieved by calculating translational displacements as a function of rotation about the DaSP in the sagittal and frontal planes [2]. These displacements can be calculated as (1) where (x_c,y_c,z_c) represents the DaSP position, (x_p,y_p,z_p) represents the NaTS position, α the pitch angle and β the roll angle.

The heave (displacement) and yaw (rotation) around the Y axis are not identified and corrected because the default configuration of the platform is not affected.

$$\begin{aligned}
Pitch:&\begin{cases} dy = \left(y_c - y_p\right)(\cos\alpha - 1) - \left(z_c - z_p\right)\sin\alpha \\ dz = \left(z_c - z_p\right)(\cos\alpha - 1) + \left(y_c - y_p\right)\sin\alpha \end{cases}\\
Roll:&\begin{cases} dy = \left(y_c - y_p\right)(\cos\beta - 1) - \left(z_c - z_p\right)\sin\beta \\ dx = \left(x_c - x_p\right)(\cos\beta - 1) + \left(y_c - y_p\right)\sin\beta \end{cases}
\end{aligned} \tag{1}$$

TABLE I: THE DEFAULT CENTER OF ROTATION OF THE PLATFORM

Plane	Sagittal plane (Pitch)	Frontal plane (Roll)
X [mm]±SD	32.4±0.7	
Y [mm]±SD	-464.6±1.1	-473.9±1.7
Z[mm]±SD		-14.3±0.6

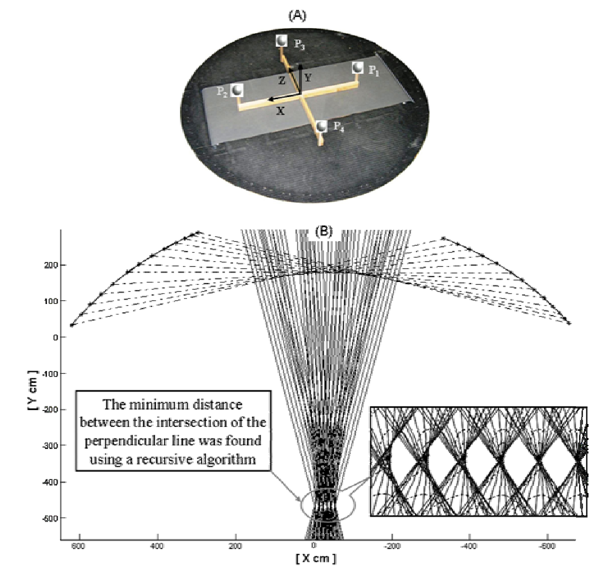

Fig. 2. (A) The Optotrak markers placed along the X and Z reference axes on the platform used for identification of the default axes. (B) The successive captured positions of the platform along the P1P2 line (dot) segments when the platform rotates in the sagittal plane.

The preliminary evaluation of this correction algorithm showed good results for simple rotational movements of the system. However, during typical trials when walking in VEs, the platform undergoes combined translation and rotation which induces undesirable movements of the DaSP caused by the mechanical constraints of the platform. Figure 3 shows the undesired DaSP displacements when typical pitch and roll rotations are combined with sway (X axis), heave (Y axis) and surge (Z axis) platform translational movements which modeled as linear equations. These equations shown in Figure 3 are integrated into the correction algorithm (1) to correct in real time the position of the DASP (xc, yc, zc).

B. Static and Dynamic Control of the Moving Platform System

The correction algorithm described above was used to correct the platform rotation movements obtained when a 26 yr-old healthy man walked in a typical VR training session. Two methods of correction were evaluated. The first is a static correction which implies that the NaTS is placed at a fixed position in the middle of the walking surface (Figure 4B). The second method consists of a dynamic correction wherein the NaTS changes in real time according to the relative position of the subject walking on the treadmill.

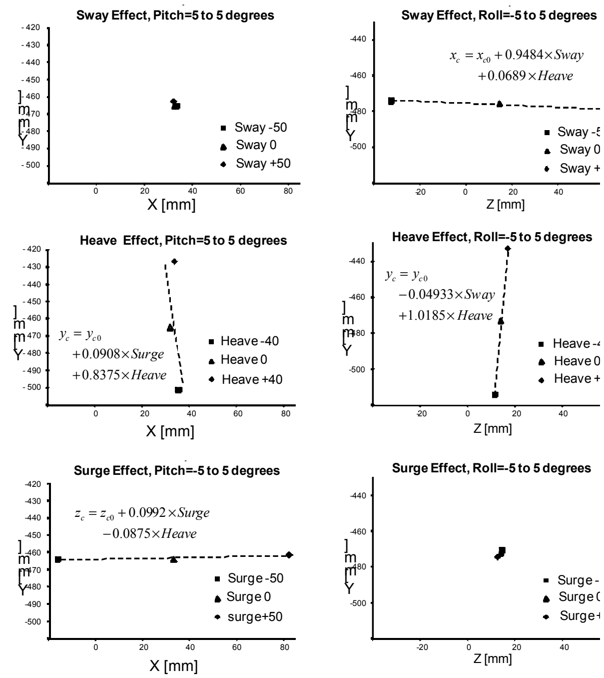

Fig. 3. Undesired displacements of the DaSP at different sway (X), heave (Y) and surge (Z) translations of the platform during -5 to 5 degrees of pitch and roll rotation movements.

Figure 4B shows the CoM (represented by diamonds) of the subject walking on the treadmill and the projection of this CoM on the walking surface (circles). It can be observed that the dynamic correction placed the NaTS about 19 cm forward of the physical middle of the walking surface with ± 6 cm of variation during this trial.

This dynamic correction based on the subject's CoM and its projection (figure 4B) could be further improved by taking into account the gait cycle and foot contacts. Figure 4A shows the typical displacement of the center of pressure (CoP) obtained when a 22 yr-old healthy male subject walked on a forceplate embedded in a special treadmill. Its displacement describes a butterfly curve in relation to the CoM in the transverse plane. Due to the high rate and amplitude of the CoP displacement this additional correction was not adopted because it is too difficult at this stage to implement given the platform response characteristics and security of the subject.

To evaluate the effectiveness of the proposed corrections, the subject walked in a typical VE scenario where combined pitch and roll rotational movements were fed to the platform according to the terrain modifications in the scene. He was asked to maintain his normal speed along the entire 40 m course. Three experimental conditions were compared in a random order: 1) 8 trials without any correction, 2) 7 trials with static correction, and 3) 7 trials with dynamic correction of the system.

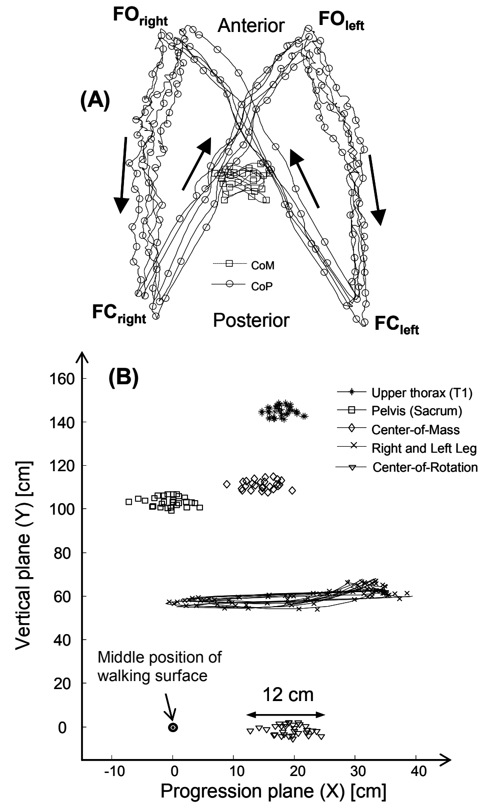

Fig. 4. (A) CoM (squares) and CoP (circles) typical displacement patterns of a subject walking on an instrumented treadmill. (B) Estimated displacement of the CoR (triangle) obtained by projecting the CoM (diamonds) of the subject to the surface of the platform. Dynamic correction mode rotates the platform around the CoR estimated position whereas static mode uses the middle position. The CoM is calculated using the Fastrak sensors placed at the trunk (stars), the sacrum (squares) and the CoM of the right and left legs (x) in the sagittal plane.

III. RESULTS

Figures 5-6 compare the results for the three conditions: without correction (dot dash line), with static (dash line) and dynamic (solid line) correction. Data is normalized with a sequence of platform movements. In figure 5, the first curve illustrates the pitch rotation during a single sequence of platform movement while in figure 6, the top curve shows the pitch rotation during the first part of two consecutive sequences of platform movements. The changes in the trunk movement and speed in the sagittal plane appear below the pitch tracing. The position of the NaTS on the surface of the platform is shown at the bottom of figures 5 and 6 for the static and dynamic corrections. The CoR without correction is not represented because it is located below the surface of the platform.

The pitch rotation in figures 5-6 corresponds in the VE scenario to a terrain change involving a downslope followed by an upslope combined with a vertical displacement to mimic walking into a depressed section of the path. As shown in the figures, application of the static and dynamic corrections led to improved subject behavior. The dynamic correction, however, led not only

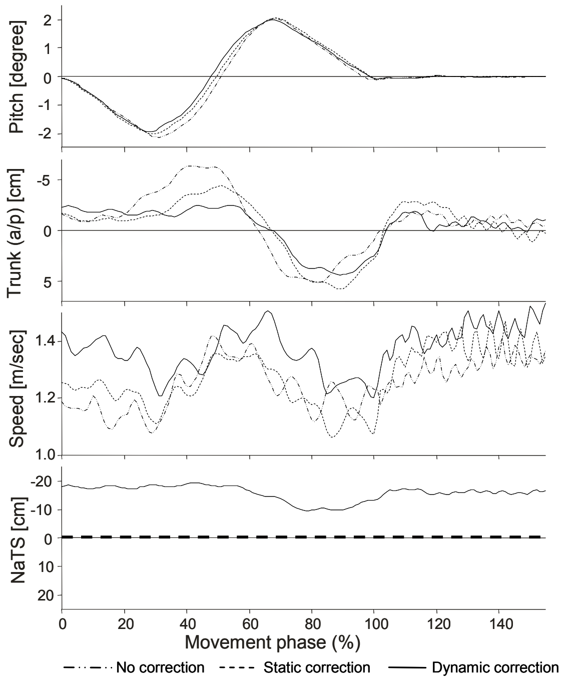

Fig. 5. Illustration of the subject responses to the first pitch rotation of the platform encountered during walking on treadmill in three conditions: dot-dash line represents the mean of the trials without correction, dash line trials with static correction, and solid line trials with dynamic correction.

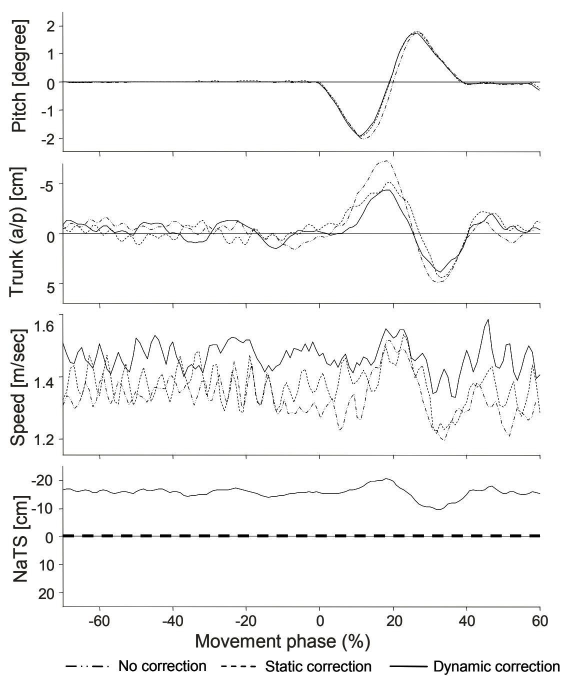

Fig. 6. Illustration of the subject responses to the pitch rotation of the platform encountered at the end of the course during walking on the treadmill in three conditions: dot dash line represents the mean of the trials without correction, dash line trials with static correction, and solid line trials with dynamic correction.

to a smoother translational movement in the progression plane but also to a smoother and faster relative speed of the subject when walking on the treadmill.

IV. CONCLUSION

The platform's default center of rotation was determined and subsequently relocated on the walking surface using the method described by Barton et al [2]. An additional correction was integrated in the algorithm to correct the undesirable displacement of the DaSP induced by the mechanical constraints of the platform. We evaluated two modes of implementation to feed appropriate movements to the platform during VEs: 1) static or 2) dynamic correction. The dynamic correction simulates more realistic subject movements as observed in figures 5 and 6 where translational trunk displacements in the progession plane are reduced combined with a smoother and faster progression speed. Moreover, the subject expressed that walking was more comfortable with the dynamic correction. In summary, these results support the application of a dynamic correction to optimize the location of the center of rotation of the platform so that subjects experience more real-world walking sensations when engaging in VEs.

ACKNOWLEDGMENTS

This work was supported by the Canadian Stroke Network, the Canadian Foundation for Innovation and the Multidisciplinary Team in Locomotor Rehabilitation (CIHR).

REFERENCES

[1] A. Lees, J. Vanrenterghem, G. Barton and M. Lake, "Kinematic response characteristics of the CAREN moving platform system for use in posture and balance research," *Medical Engineering & Physics*, Vol. 29, no. 5, pp. 629-635, June 2007.

[2] J. G. Barton, J. Vanrenterghem, A. Lees, and M. Lake, "A method for manipulating a movable platform's axes of rotation: a novel use of the CAREN system," *Gait and Posture*, Vol. 24, no. 4, pp. 510-514, 2006.

[3] J. Fung, F. Malouin, B. J. McFadyen, F. Comeau, A. Lamontagne, S. Chapdelaine, *et al.*, "Locomotor rehabilitation in a complex virtual environment," in *Proc. 26th Annual International Conference of the IEEE EMBS*, San Francisco, pp. 4859-4861, Sept. 2004.

[4] J. Fung, C. L. Richards, F. Malouin, B. J. McFadyen and A. Lamontagne, "A treadmill and motion coupled virtual reality system for gait training post-stroke," *CyberPsychology & Behavior*, vol. 9, no. 2, pp. 157-62, 2006.

[5] F. Malouin and C. L. Richards, "Assessment and Training of Locomotor Function after Stroke: Evolving Concepts," in *Science-Based Rehabilitation: Theories into Practice*, K. M. Refshauge, L. Ada, E. Ellis, Sydney: Butterworth-Heinemann, pp. 185-222, 2005.

[6] B. J. McFadyen, F. Malouin, J. Fung, F. Comeau, S. Chapdelaine, C. Beaudoin, *et al.*, "Development of Complex Virtual Environments for Locomotor Training Following Stroke," presented at the 15th ISEK Symposium, Boston, June 2004.

[7] D. Stewart, "A Platform with Six Degrees of Freedom," in *Proc. Institution of Mechanical Engineers*, London, Vol. 180, pp. 371-86, 1965.