

# Sensorimotor Enhancement with a Mixed Reality System for Balance and Mobility Rehabilitation

Joyce Fung, PhD, PT, and Claire F. Perez, MSc, PT

**Abstract**—We have developed a mixed reality system incorporating virtual reality (VR), surface perturbations and light touch for gait rehabilitation. Haptic touch has emerged as a novel and efficient technique to improve postural control and dynamic stability. Our system combines visual display with the manipulation of physical environments and addition of haptic feedback to enhance balance and mobility post stroke. A research study involving 9 participants with stroke and 9 age-matched healthy individuals show that the haptic cue provided while walking is an effective means of improving gait stability in people post stroke, especially during challenging environmental conditions such as downslope walking.

## I. INTRODUCTION

THE current state of knowledge in rehabilitation emphasizes the need for task-specific repetitions to promote the re-acquisition of motor skills [1-4]. Loss of mobility and upright balance control resulting in falls represents a major health problem for older adults and stroke survivors. The inability to walk is one of the more devastating consequences of stroke and regaining ambulatory independence is the most common rehabilitation goal expressed by stroke patients [5]. A major gait dysfunction encountered in both older and post-stroke populations and targeted during rehabilitation is the difficulty in overcoming environmental barriers such as surface changes, slopes and obstacles [6,7]. In walking tasks that are more challenging such as slope walking, the sensorimotor demands are increased and necessitate specific modifications i.e. changes in gait pattern and rapid postural adjustments [8,9]. Older individuals and people post-stroke lack this flexibility in walking ability and therefore cannot readily adapt to the increased task demands. Gait re-training after stroke thus requires intensive task-related practice as well as variable practice in changing environmental contexts with increasing physical demands [10]. Sufficient practice

and patient empowerment are equally important in the rehabilitation process. It is difficult to meet these criteria for the practice of locomotor tasks in currently constrained indoor and outdoor settings.

Virtual reality (VR) technology provides the opportunity to optimize motor relearning. Extensive human and animal studies have shown that, following a CNS lesion, improvements in sensorimotor functions result from experience-dependent neuroplasticity [11] which can be achieved through salient, repetitive, intensive and motivating practice, with demanding and varied environmental contexts, as well as increased patient empowerment [12]. VR is a computer-based, 3D interactive simulation that occurs in real-time. It refers to a range of computing technologies that present artificially generated sensory information (from vision and proprioception) in a form that people perceive as similar to real-world objects and events [13, 14]. The term virtual environment (VE) is used to describe the simulation of a visual 3-D environment presented to the subject via a display system. In a VE, the simulated objects and events are not only sensed, but the user can anticipate and react to them as though they were real [15]. The technology, with the capacity of simulating environments, offers a new and safe way to not only increase practice time but also to offer the varied environments and controlled constraints needed to maximize learning. It allows patients to be exposed to more complex physical environments (both indoors and outdoors) including environmental hazards without physical danger. VR also provides a gaming environment to motivate patients to adhere to training. VR can thus be used to both control and enhance specific real-world and environment-person interactions, so as to empower and motivate patients as they attempt challenging tasks without real hazards.

VR systems can be combined with the manipulation of physical environments and sensory feedback to create a mixed reality system for multisensory integration and sensorimotor enhancement. For instance, haptic cues can serve as a reference source for postural orientation by ‘anchoring’ the body position with respect to the environment through enhanced proprioception and the perception of earth’s vertical position [16]. The term haptics refers to the sense of touch and is usually applied to the hand/fingers ability to explore, detect and perceive specific environmental features. Haptic touch has emerged as a novel and efficient technique to improve postural control and dynamic stability in humans [17]. We have developed a

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J Fung is Associate Professor and William Dawson Scholar with the School of P & OT, McGill University, and Director of Research with the Feil/Oberfeld/CRIR Research Centre of the Jewish Rehabilitation Hospital (JRH) in Montreal, Quebec, Canada. (corresponding author phone: 450-688-9550 ext. 529; fax: 450-688-3673; e-mail: joyce.fung@mcgill.ca).

C. F. Perez is Faculty Lecturer with the School of P & OT, McGill University, and PT research associate and Advanced Practice Leader with the JRH (e-mail: claire.perez@mail.mcgill.ca).

mixed reality system incorporating VR, surface perturbations and light touch [18] for rehabilitation purpose. The evidence of enhancement of balance and mobility functions post stroke with such a system will be presented in this minisymposia paper.

## II. MATERIALS AND METHODS

### A. Instrumentation

We have developed an advanced locomotor system (Fig. 1A) which combines the use of virtual reality (VR) with a self-paced treadmill mounted on a motion platform [18]. The motorized treadmill is servo-controlled by the output of an electropotentiometer which is tethered to the walking person, such that the walking speed can be adjusted instantaneously and voluntarily. The motion platform is servo-controlled by 6 electrohydraulic actuators to simulate sudden or gradual terrain changes in 6 axes or degree-freedom-of movement. An animated scene is rear-projected onto a screen (2.5x3.2m) placed 1.3m in front of the treadmill. A specialized software, Computer Assisted Rehabilitation ENvironment (CAREN-3, MOTTEK BV) [19] controlled and synchronized the instantaneous treadmill speed with the VR scene progression and the platform movement. Subjects don a safety harness and polarized glasses to have 3D perception of the VE that presents challenges related to physical (obstruction and surface angle), temporal (speed requirements, speed of moving obstacles) and cognitive (attention, planning) characteristics of locomotion. Previous results [18] showed that healthy subjects were able to have full control of their own walking speed both on the treadmill and within the VE, while experiencing a strong sense of presence. The VR scene shown in Fig. 1B was that of a 40-meter, clearly delineated outdoor walking path set amidst grass and trees.

A haptic bar was specially designed to provide somatosensory information through fingertip contact with an external surface (Fig. 1C). The development and feasibility of the device to provide augmented cues have been reported previously [20]. The bar (1cm x 1cm x 45cm) was instrumented with load sensor (Interlink Electronics [21]) embedded on the lateral aspect to measure the pressure exerted by the index fingertip. The bar could be adjusted in height and mounted on the right or left side of the walking subject. The strip was calibrated prior to use against known weights to verify output validity and to check for hysteresis. The analog 3D force data from the instrumented cane were sampled at 1200 Hz. The haptic strip load sensor data were converted to force (N). All force values were then expressed as a proportion of the body mass of the individual (% body weight).

### B. Subjects

A total of 9 persons (65±5 y.o.) with a chronic stroke (≥ 1 year) and 9 healthy controls matched in gender and age

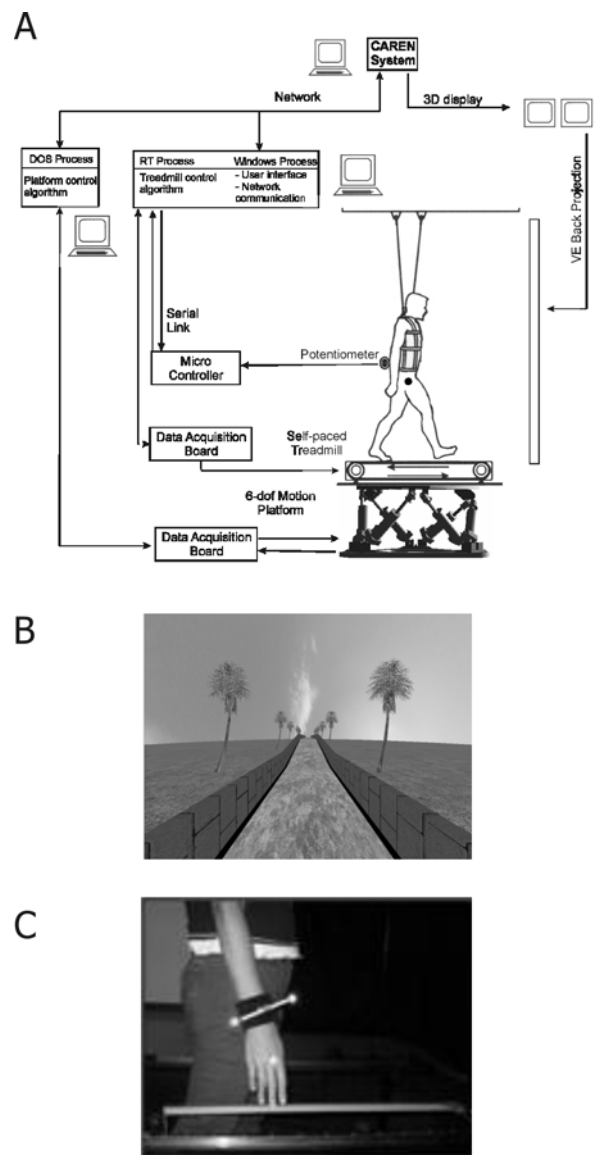


Fig. 1. A) Schematic setup of the treadmill-based VR system. B) Example of an outdoor virtual scenario. C) The haptic bar instrumented on the side of the treadmill.

(66±4 y.o.) participated in this study. Inclusion criteria for the stroke group included people with a single, uni-hemispheric cerebral lesion, independent ambulation without a walking aid for a minimum of 40m and persisting gait difficulties. Additionally, subjects were excluded if they (1) were greater than 80 years old secondary to the greater potential of peripheral sensory nerve impairment and (2) had language, cognitive or perceptual impairments affecting their ability to understand and follow instructions. Subjects with impaired light touch sensation of the non-paretic (stroke group) or dominant (healthy group) fingertips and/or hand were excluded from the study.

### C. Outcome measures

Forty-two reflective markers were positioned on body landmarks. Kinematic data were acquired at 120 Hz using a

6-camera Vicon MX motion analysis system (Oxfordmetrics, UK). Anthropometric data were taken prior to data collection and the total body's centre of mass (COM) in 3D was computed with the Plug-in-Gait model of the Vicon motion analysis system. The main outcomes of interest reported in this paper is gait variability measured by the percentage coefficient of variation in the stride duration (% CV), step width and gait speed. To calculate the stride-to-stride variability, the kinematic data were batch-processed with a customized computer script in Matlab (Mathworks Inc., USA) to determine the gait events of initial foot contact and foot-off for each limb, based on the sagittal plane foot trajectory. Measures of gait variability have been found to be more sensitive than direct gait measures such as gait speed and therefore provide more precise indices of walking performance [22]. Less variability in a gait parameter such as stride duration would indicate a more rhythmic and stable gait. It is suggested that measures of variability may also reflect qualitative aspects of gait otherwise overlooked by measuring gait speed alone. Stride duration was defined as the time taken between 2 consecutive initial foot contacts of the same limb (one gait cycle). The % CV was computed as a percentage of the standard deviation of stride or cycle duration over the mean. Step width was defined as the distance (cm) between the left and right limb heel marker distance when in the double support phase of gait. Step width is often related to dynamic stability in the frontal plane such that decreases in width represent greater balance stability and improved postural control. The overground gait speed was measured with the 10-meter walk test, whereas gait speed within the VE was calculated using the instantaneous treadmill speed output from the motor as recorded by the CAREN software. The gait cycles occurring in the middle 20 meters of level walking and during the 20 meters of slope walking were retained for analysis.

#### D. Protocol

The experimental protocol involved three walking surface conditions including level, up-slope (5°) and down-slope (5°) and two touch conditions: no touch (NT) or light touch (LT). The presentation order of the walking conditions was randomized between 2 baseline trials (NT level walking). Rests were provided as necessary during both the habituation and the experimental phases. Habituation to walking on the treadmill without support, using light fingertip touch, and walking on inclined surfaces and viewing the virtual scene were all performed prior to data collection. During habituation to the LT condition, real-time feedback of the loading pressure on the haptic strip was used to train the subject to apply a fingertip contact force of less than 4N while walking. No other specific training or instructions were provided.

### III. RESULTS AND DISCUSSION

Persons with stroke generally have difficulty coordinating and stabilizing their body movements while walking in the VE, as shown by the COM traces plotted in 3D (Fig.2). Their overall coordination lacks the smooth multiphasic control observed in healthy subjects. Contrary to the tight control (depicted by decreased COM excursions in all 3 planes) observed in healthy subjects as an adaptive strategy for balance or stability control as they go from level walking to incline (up- or downslope) walking, people with stroke show increased COM mediolateral excursions walking. The addition of light touch results in decreased excursions especially in the mediolateral direction, indicating tighter control.

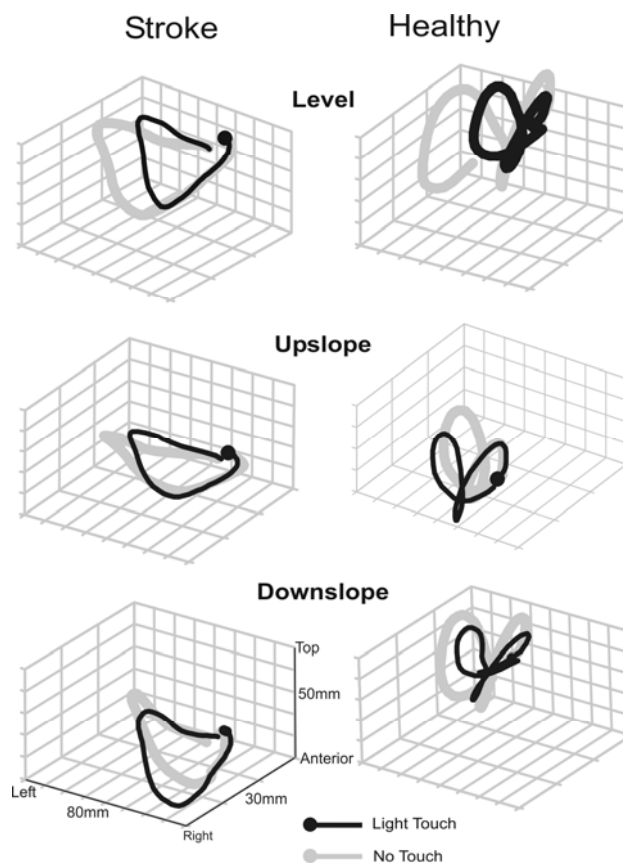


Fig. 2. Representative centre of mass trajectories in 3D (axes of directions highlighted on bottom left graph) from one person with stroke and one healthy individual under different haptic conditions. The beginning of the gait cycle is indicated by the filled circle in the centre.

Based on this observation, a vector space analysis (VSA) approach was used to quantify the coordination of the body's CoM position during self-paced treadmill locomotion. The COM was computed in 3D and normalized in time to the stride cycles (as depicted by the toe trajectories) of the individual paretic limb (for stroke participants) or the equivalent right/left limb (for healthy controls). CoM velocity was obtained by differentiating CoM position in time, and smoothed with a low-pass filter

of 10 Hz. The VSA involves plotting 3D velocity vectors along with 3D mean CoM trajectory points to construct a 3D phase diagram that embeds the 6D data set. This output is essentially a 3D plot of the velocity-position coordination of CoM (Fig. 3). The 3D velocity vector projections in each axis across the gait cycle were then squared and averaged. The mean sums of squares were then calculated for each direction and summed to represent the mean total kinetic energy of the CoM related to the unit mass, which can be simply defined as the mean circulation of the 3D velocity vectors over the CoM loop, according to the VSA approach. It can be seen from the VSA plots (Fig. 3) that the CoM velocity vectors of the person with stroke are markedly increased in the mediolateral direction as compared to the healthy control, indicating a compromise in mediolateral stability. Indeed, unpaired Student's t-tests comparing the mean sums of squares of the velocity vectors between the two subject groups revealed a significant increase in the mediolateral direction ( $p=0.004$ ) and decrease in the vertical direction ( $p=0.009$ ) in stroke participants. However, the mean total kinetic energy was not significantly different between groups.

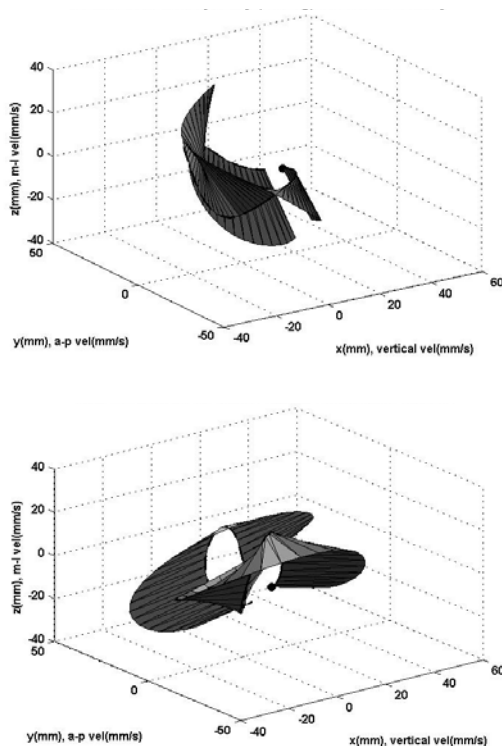


Fig. 3. Representative VSA plots for a post-stroke (top) and a healthy (bottom) individual. The beginning of the gait cycle is indicated by the filled circle in the centre.

Along with the difficulty of postural stabilization during gait, persons with stroke also show marked variability in their stride durations, but this can be alleviated to a certain extent with light touch. Fig. 4 compares stride duration variability between the 2 groups of subjects across different slope and touch conditions. A 3-way ANOVA revealed main effects due to group ( $p=.0003$ ), walking surface condition ( $p=.007$ ) as well as an interaction effect between walking surface and touch conditions ( $p=.02$ ). Post-hoc Tukey tests identified a significant difference ( $p=.007$ ) between the NT and LT conditions during down-slope walking in the stroke group.

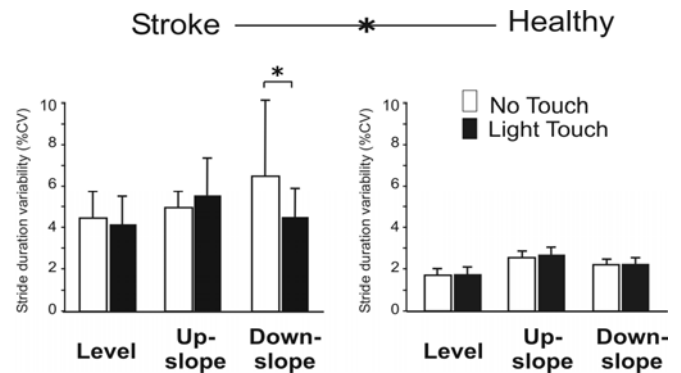


Fig. 4. Mean % CV for stride duration and standard deviation for all conditions in the post-stroke (paretic limb) and healthy (left limb) groups of subjects. Asterisks indicate significant differences revealed by ANOVA and posthoc comparisons.

A 3-way ANOVA conducted on the step width also revealed a main effect due to group ( $p=.009$ ) along with a main effect due to touch ( $p=.00003$ ). The step width in subjects with stroke is significantly larger than healthy individuals. Further examination with Tukey tests revealed that the step width for people in the post-stroke group in both LT ( $p=.002$ ) and C ( $p=.0001$ ) conditions were significantly reduced compared to the NT condition.

Main effects due to group ( $p=.0005$ ) and walking surface condition ( $p=.001$ ) were also revealed for gait speed with a 3-way ANOVA. The speed of walking on the level surface was significantly greater compared to both up-slope ( $p=.002$ ) and down-slope ( $p=.009$ ) walking for both groups regardless of touch conditions. During the more challenging tasks of either up- or down- slope walking, gait speed was decreased compared to the level surface regardless of touch condition. Interestingly, the lowest gait speeds in each group were obtained under different walking surface conditions (down-slope for the post-stroke and up-slope for the healthy group).

The effects due to light touch could not be attributed to any difference in forces applied on the non-paretic or dominant fingertip. There was no significant difference between groups in the amount of finger pressure. The mean load exerted on the haptic strip was below 1% body weight in both groups.

#### IV. CONCLUSION

As a proof of principle, a mixed-reality system incorporating virtual reality, real physical challenges and augmented haptic input can be utilized for balance and gait rehabilitation post stroke. Beneficial effects on balance and gait stability post-stroke are observed when additional somatosensory information in the form of a light fingertip touch, especially when walking in challenging conditions such as inclines. Light touch input alone without any mechanical support can produce gait improvements in people with stroke. A different type of sensory input or haptic cane may be devised for this population whereby longer ground contact time is facilitated. Further research to explore these and other possible clinical implications for the use of haptic input to improve gait post-stroke is required.

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#### REFERENCES

- [1] F. Malouin, M. Potvin, J. Prévost, J. C. L. Richards, and S. Wood-Dauphinee, "Application of an intensive task-oriented gait training program: case report in a series of acute stroke patients," *Phys. Ther.*, vol. 72, pp. 781-793, 1992.
- [2] Richards C.L., Malouin F., Wood-Dauphinee S., Williams J.I., Bouchard J.P., and Brunet D. "Task-specific physical therapy for optimization of gait recovery in acute stroke patients," *Arch. Phys. Med. Rehabil.*, vol. 74, pp. 612-620, 1993.
- [3] Richards C.L., Malouin F., and Dean C.M. "Gait in stroke: assessment and rehabilitation," *Clin. Geriatr. Med.*, vol. 15, pp. 833-855, 1999.
- [4] C. M. Dean, C. L. Richards, and F. Malouin, "Task-related circuit training improves performance of locomotor tasks in chronic stroke: a randomized, controlled pilot trial," *Arch. Phys. Med. Rehabil.*, vol. 81, pp. 409-417, 2000.
- [5] S. E. Lord, K. McPherson, H. K. McNaughton, L. Rochester, and M. Weatherall, "Community ambulation after stroke: how important and obtainable is it and what measures appear predictive?" *Arch. Phys. Med. Rehabil.*, vol. 85, pp. 234-239, 2004.
- [6] M. Gerin-Lajoie, C. L. Richards, and B. J. McFadyen, "The circumvention of obstacles during walking in different environmental contexts: a comparison between older and younger adults," *Gait Posture*, vol. 24, pp. 364-369, 2006.
- [7] E. De Bujanda, S. Nadeau, D. Bourbonnais, and D. R. Dickstein, "Associations between lower limb impairments, locomotor capacities and kinematic variables in the frontal plane during walking in adults with chronic stroke," *J. Rehabil. Med.*, vol. 35, pp. 259-264, 2003.
- [8] A. Leroux, J. Fung, and H. Barbeau, "Postural adaptation to walking on inclined surfaces: I. Normal strategies," *Gait Posture*, vol. 15, pp. 64-74, 2002.
- [9] A. McIntosh, K. T. Beatty, L. N. Dwan, and D. R. Vickers, "Gait dynamics on an inclined walkway," *J. Biomech.*, vol. 39, pp. 2491-2502, 2006.
- [10] 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, Eds. Sydney: Butterworth-Heinemann, pp 185-222, 2005.
- [11] J.A. Kleim and T.A. Jones, "Principles of experience-dependent neural plasticity: implications for rehabilitation after brain damage," *J Speech Lang. Hear. Res.*, vol. 51, pp. S225-S239, 2008.
- [12] R. Teasell, N.A. Bayona, and J. Bitensky, "Plasticity and reorganization of the brain post stroke," *Top. Stroke Rehabil.*, vol. 12, pp. 11-26, 2005.
- [13] R. S. Kalawsky, *The science of virtual reality and virtual environment*. Wokingham: Addison-Wesley, 1993.
- [14] Rheingold H. *Virtual reality*. London: Secker & Warburg, 1991.
- [15] Steuer J. "Defining virtual reality: dimensions determining telepresence," *J. Commun.*, vol. 2, pp. 17-27, 1992.
- [16] J.J. Jeka, R.D. Easton, B.L. Bentzen, and J.R. Lackner, "Haptic cues for orientation and postural control in sighted and blind individuals," *Percept. Psychophys.*, vol. 58, pp. 409-423, 1996.
- [17] M. Baccini, L. A. Rinaldi, G. Federighi, L. Vannucchi, M. Paci, and G. Masotti, "Effectiveness of fingertip light contact in reducing postural sway in older people," *Age Ageing* vol. 36, pp. 30-35, 2007.
- [18] 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," *Cyberpsychol. Behav.*, vol. 9, pp. 157-162, 2006.
- [19] MOTEK CAREN-Computer Assisted Rehabilitation Environment Available: <http://www.motekmedical.com>
- [20] C. Perez and J. Fung, "An instrumented cane devised for gait rehabilitation and research," *J. Phys. Ther. Ed.*, vol. 25 pp. 37-41, 2011.
- [21] Inter Link Electronics. Available: <http://www.interlinkelectronics.com>
- [22] J. Hausdorff J, "Gait variability: methods, modeling and meaning," *J. NeuroEngin. Rehabil.*, vol. 2, section 19, 2005.