**S. 1. Monday June 30, 12:30 – 14:30**

## Uncovering real-life falls

Chair and discussant: prof. Chris Todd, University of Manchester, UK

**Stephen Robinovitch,** Simon Fraser University, Canada

### What we've learned from video-based recording of falls in older people residing in long-term care

Video capture of falls in the high-risk long-term care (LTC) setting can provide insight on the biomechanical, situational, and environmental factors that contribute to these events, to help guide the design of interventions. Since 2007, the Technology for Injury Prevention in Seniors program has partnered with two LTC centres in the Vancouver area to record video footage of 1074 falls experienced by 358 individuals, from networks of digital video cameras (n=270) in common areas (hallways, dining rooms, lounges). Individuals captured falling have a mean age of 81 years (SD=9), and 60% are female. We have consent to access medical records in 160 fallers with 602 video-captured falls. Of these, 43% have hypertension, 61% have dementia, 22% have diabetes, 15% have a history of stroke, and 3% have Parkinson's Disease. Over 50% are taking antipsychotics, antidepressants, and/or analgesics. We have analyzed each video to categorize key aspects of fall initiation, descent and impact, using a validated 24-item questionnaire (Yang et al., BCM Geriatrics, 2013). In terms of fall initiation, we have focused on describing the scenarios that lead to falls in LTC (Robinovitch et al., Lancet, 2013). Key observations include (1) the high prevalence of falls due to incorrect weight shifting (41% of all falls) followed by tripping (23%) and loss-of-support with an external object (11%), (2) the similarity in the frequency of falls occurring while transferring and walking, and (3) the finding that, while 74% of individuals were habitual users of walkers and wheelchairs, only 21% of falls occurred while using these devices. In terms of fall descent, we have focused on fall direction and balance recovery attempts. 46% of falls involved attempts to recover balance by stepping, and 23% by grasping a nearby object. Most falls were directed backwards (39%), followed by sideways (28%), forward (17%), and straight down (16%), but there was a marked tendency for individuals to rotate backwards during descent. In terms of fall impact, we have examined the consequences of falls in terms of the impacting body sites, and resulting injuries. Of note, head impact was observed in 37% of cases (Schonnop et al., CMAJ, 2013). Probability for head impact did not associate with hand impact (which occurred in 74% of cases), was highest in forward falls, and associated with hypertension and impaired vision. While head injury was documented in 34% of cases (lacerations, abrasions or hematoma), no concussions were noted. These results suggest several new opportunities for prevention of falls and injuries in LTC, including exercises to enhance transferring and upper limb protective responses, improvements in mobility devices (e.g., self-locking wheelchairs, universal design walkers), advances in the management of medications and visual impairments, improved screening for traumatic brain injury following falls, and environmental modifications such as compliant flooring. In moving forward, the challenge is develop effective methods for linking the video evidence with the clinical and situational context, and sharing that information with stakeholders to drive improvements to fall injury prevention.

**Lorenzo Chiari, Universita' di Bologna, Italy**

**What we've learned by recording falls with wearable inertial sensors**

Wearable inertial sensors offer a remarkable opportunity to measure body movements in a first-person perspective. The kinematics of body segments to which they are attached can indeed be measured at a reasonably low cost, in terms of intrusiveness and acceptability, and with a more than adequate accuracy. Furthermore, being body-worn they can provide measures even in unstructured environments and outdoor. For these reasons the usage of inertial sensors has been so popular in the field of automatic fall detection. Many different approaches have been explored to solve the fall detection problem using only accelerometers or inertial measurement units (both gyroscopes and accelerometers). Nevertheless, as pointed out in a recent systematic review promoted by the FARSEEING Consortium (Schwickert et al, Z Gerontol Geriat, 2013) which analyzed 96 papers published between 1998 and 2012, the sensor-based devices and their technical specifications varied considerably across studies. Most of the devices included triaxial or bi-/uniaxial accelerometers. Sampling rates and measurement ranges of the sensors were very heterogeneous. The placement of the devices depended on the different sensor types and the number of sensors used for each setting. The most frequent sensor placement positions were waist or hip, followed by trunk attachment; some studies reported combined placement positions. Most publications presented simple detection models with algorithms based on the recognition of a fixed threshold. In some cases these algorithms applied machine learning methods to a minimum of two combined detection phases (e.g. impact and postfall). The findings further indicate a minimal number of analysed real-world falls and thus the lack of a published evidence base for the existing commercially available fall detection devices. This demonstrates an almost embryonic state of research. Most articles are case reports, case-series or convenience samples and 90/96 depended on simulated falls by younger volunteers rather than real falls amongst elderly people. Algorithmic approaches based on these data, which have been developed using simulations of real-world falls are therefore clearly open for further improvement. As recently outlined by Bagalà et al. (PLoS One, 2012), algorithms calculated from fall simulations in healthy young subjects lack the necessary accuracy requirements for real-world fall detection. They lack either sufficient sensitivity or specificity and would thus produce a high false alarm rate. Contextual information of the fall event such as time, location or prefall activity is scarcely documented. In addition, the mechanisms of the falls are not known as they could not be accurately documented, as yet. With the objective of dealing with the missing evidence base in falls research, the FARSEEING project has started collecting real-world falls by means of wearable sensors. A consensus has been reached and recommendations released on fall definition, fall reporting (including fall reporting frequency, and fall reporting variables), a minimum clinical dataset, a sensor configuration, and variables to describe the signal characteristics (Klenk et al., Z Gerontol Geriat, 2013). From the first 150 falls that were collected we could start the extraction of temporal and kinematic parameters to inform the development of future fall detection algorithms (Bourke et al, ISPGR 2014) and are learning the first rudiments on the ‘why’ and ‘how’ such a common but still unexplored process affects the life of millions of elderly each year.

**Clemens Becker,** University of Stuttgart, Germany

**Which are the major knowledge gaps that we still need to fill in falls research**

Fall risk and fall prevention research has made considerable progress over the last years but some major knowledge gaps remain. These gaps include conceptualization, analysis of real world fall events, fine tuning and targeting of interventions and finally knowledge translation into large scale programs reaching the population. In a fall phase model we published in 2012 we argued that it is useful to separate the fall into five phases (Becker et al, ZGG, 2012). The analysis of the pre-phase including near fall episodes and gait and transfer abnormalities is likely to increase our knowledge on risk factors for falls and intervention approaches. Time scale analysis of fall prediction using body worn sensors is likely to improve the understanding of precipitating fall risk factors along with video footage and other life logging approaches. Structured detailed fall interviews are complimentary to understand contextual factors in this respect. Video footage is essential to improve the understanding of balance and fall responses during the falling phase. This can lead to improved furniture ergonomics, walking aid and wheelchair design. Currently, a lot of the assumptions rely on lab experiments with healthy subjects on perturbation platforms. Body worn sensors can guide the design of training interventions. The analysis of impact signals can e.g. stimulate product development of protective clothing, absorbing floor materials. Closer looks at the resting and recovery phase are essential to improve home alarm systems and fall detection algorithms to reduce false alarms and thereby enhance adherence. Up to now, most epidemiological studies use fall and faller rates as endpoint. A closer look including long-term monitoring with sensor technology is likely to result in a much more detailed analysis leading to differing approaches. Near fall and impact analysis, presence or absence of falling and landing responses, differing impact signals and recovery response will lead to a variety of options for new intervention strategies or targeting. The 2012 Cochrane Reviews demonstrate that we need different intervention strategies for community dwelling persons with or without need of assistance. Hospital, rehabilitation and long-term care institutions need to implement programs according to their specific needs. In this area major gaps are translational deficits and slow implementation into large scale efforts. This needs to be accompanied by evaluation to identify dilution effects and ineffective implementation to redesign components. It is promising that several large scale European networks such as ProFound, E-no falls, and Farseeing are underway to fill some of these gaps and similar activities are underway in North America and Australasia. Using these synergies it is likely that a lot of the missing links will be available in the next five years mainly supported by using ICT approaches.

**Stefania Bandinelli,** Azienda Sanitaria di Firenze, Italy

**Why 2 out of 3 older subjects living in the community do not fall? The FARSEEING-InChianti study**

InCHIANTI-study is a population based epidemiologic study conducted in the Chianti region of Italy to investigate age-related decline in mobility (Ferrucci et al, JAGS, 2000). The ability to walk provides the basis of mobility but is not a synonymous. Natural environment commonly imposes varied challenges while walking. The new models of disability suggest that it is the inability to accommodate these environmental demands on mobility that leads to mobility disability. Adaptation to the environment requires the ability to switch rapidly across motor strategies and modify *in itinere* the motor program. Thus, not surprisingly, deficits in attention and executive function processes are independently associated with risk of postural instability, impairment in activities of daily living, and falls. Higher gait variability has been described in older adults with frailty, Parkinson’s and Alzheimer’s disease, and prospectively associated with a high risk of future falls and mobility decline. Interestingly, high stride time gait variability has been shown to predict future falls in community-dwelling older adults, even when gait velocity failed to demonstrate an association. Usual gait speed and brisk walking test are measure of walking ability commonly used in epidemiological studies that have been associated with mobility outcomes and disability in older adults. Personal risk factors for falls vary considerably by location and activity at the time of the fall. Because traditional performance tests are unable to assess how individuals cope with daily challenges posed by the environment, we introduced in the mobility assessment protocol movement sensors implemented in a commercial smartphone (SP) that allows the measure of many different components of movement activity in real life during a 5-days recording in a community dwelling population.The InCHIANTI-FU4 Study has enrolled so far a sample of 376 survivors (S) from Baseline-cohort (285 S ≥ 65yrs). Protocol of the study include the collection of demographic, health, behavioural, mobility, mood and cognitive, biological and metabolic information using a set of validated instruments and scales (home interview, medical examination, mobility performance assessment, biological samples collection, instrumental laboratory tests). The FARSEEING project has allowed implementing some of the mobility tests included in the original InCHIANTI protocol by recording signals of three different sensors built in common SP placed in a pocket and positioned by a belt on the back. Moreover participants have been invited to wear SP for 7 days during their daily activities. Furthermore, S were asked to evaluate feasibility and usability of SP. S have been monitored to detect the occurrence of falls by a monthly telephonic-follow-up for 6 months at then at 1 year. Data collection is almost completed. 125/285 S have been evaluated by FARSEEING-InCHIANTI protocol while 105/125 S (85%) have agreed to wear SP for a week. Mobility characteristics derived by SP signal-recording of such a low-risk population will be presented. Based on this experience we support the idea that SP-Technology enables measuring the real mobility activity during the daily life in older subjects and contributes to define the personal risk profile for falls that could not captured by usual gait speed tests in laboratory.

**S. 2. Monday June 30, 12:30 – 14:30**

**Can (biomechanical) mobility parameters serve as a biomarker for neurodegenerative movement disorders?**

**Walter Maetzler,** University of Tuebingen, Germany

Alice Nieuwboer, KU Leuven, Belgium

Biomarkers for neurodegenerative movement disorders: state of the art and central concepts

According to the Biomarkers Definition Working Group[1] a biomarker is an objectively measured characteristic that serves as an indicator of normal biological processes, pathogenic processes, or responses to treatment intervention. Throughout the literature, the term biomarker and related concepts are often ill-defined. We will start this symposium. by defining related terms such as sensitivity, specificity, predictive value, validity, as well as biomarkers for susceptibility and (early) detection of a disease (trait), for diagnosis (state), prognosis (rate), and prediction of treatment effects. Parkinson's disease (PD) will be used as a disease model to present illustrative examples of such markers. In neurodegenerative movement disorders in general, and PD in particular, it is crucial that biomarkers indicate true disease processes rather than compensatory changes. Also, in a complex disease such as PD, a combination rather than a single biomarker is likely to achieve better sensitivity and specificity for classifying at risk individuals, identifying phenotypes with and without cognitive decline and predicting disease progression. Besides molecular, cellular and genetic biomarkers, the detection of prodromal motor or other signs possibly complemented with imaging methods are likely to be part of the different types of PD biomarkers. While biological, clinical or economic considerations will initially provide the foundation for adoption of a specific biomarker, ultimately, robust validation through power-based clinical trials and statistical analysis are essential. After establishing a potential biomarker, independent cross-validation studies are needed to prospectively determine its predictive accuracy while adjusting for confounding factors. Diagnostic and prognostic biomarker development in movement disorders has to allow sensitive and specific risk-stratification within a sufficiently wide 'window of opportunity' for disease-modifying treatment approaches to be effective.

[1]Biomarkers Definition Working Group. Biomarkers and surrogate end points: preferred definitions and conceptual framework. Clin Pharamcol Ther 2001; 69:89-95.

**Fay Horak, Oregon Health and Science University, USA**

**Yes, (biomechanical) mobility parameters can serve as a biomarker for neurodegenerative movement disorders.**

Balance and gait impairments characterize progression of Parkinson's disease (PD), predict fall risk, and are important contributors to reduced quality of life. Advances in technology of small, body-worn inertial sensors have made it possible to develop quick, objective measures of balance and gait impairments in the clinic for research trials and clinical practice. Objective balance and gait metrics may eventually provide useful biomarkers for PD. In fact, objective balance and gait measures are already being used as surrogate end-points for demonstrating clinical efficacy of new treatments, in place of counting falls from diaries, using stop-watch measures of gait speed, or clinical balance rating scales. Many objective measures of balance and gait for PD have already been shown to be valid, reliable, sensitive to early disease, related to progression compared to clinical gold-standards such as the UDPRS, and responsive to interventions such as levodopa and deep brain stimulation (DBS). This talk summarizes the types of objective measures sensitive to PD and to levodopa intervention from body-worn sensors. However, identification of balance and gait metrics that are insensitive to levodopa will be most helpful for future neuroprotective trials. We organize the metrics based on the neural control system for mobility affected by PD: postural stability in stance, postural responses, gait initiation, gait (temporal-spatial lower and upper body coordination and dynamic equilibrium), postural transitions, and freezing of gait. However, the explosion of metrics derived by wearable sensors during prescribed balance and gait tasks that are abnormal in people with PD do not yet qualify as behavioral biomarkers because many balance and gait impairments observed in PD are not specific to the disease, nor shown to be related to specific pathophysiologic biomarkers. In the future, the most useful balance and gait biomarkers for PD will be those that are sensitive and specific for early PD and related to the underlying disease process.

**Martijn Müller, University of Michigan, USA**

**No, (biomechanical) mobility parameters likely cannot serve as a biomarker for neurodegenerative movement disorders**

An ideal biomarker may serve both as a marker of existing pathology and of pathology progression over time. Using Parkinson's disease as a model, this talk will discuss why it is unlikely that a single biomechanical measure can reach the level of biomarker. Current technology allows for relatively simple assessment of postural instability and gait difficulty (PIGD) features of PD in both the laboratory as well as the natural environment. This would make it an ideal candidate for biomarker selection. The hallmark pathophysiology of Parkinson's disease (PD) is nigrostriatal dopaminergic denervation. However, PD is a multisystem neurodegenerative disease characterized by both monoaminergic and cholinergic system degeneration and white matter lesions and Alzheimer-type pathology (β-amyloid) can often be superimposed on PD-related pathology. The onset of these pathologies is variable and heterogeneous; for example white matter lesions and β-amyloid may not affect all PD patients. Although research studies have shown that all of these pathologies associate with PIGD features they also associate with other symptoms of PD. Thus, a complex picture of multisystem pathology emerges that affects many aspects of motor and non-motor PD features. Simple biomechanical measures may serve as an endpoint marker of overall pathology and disease progress; however, given the complexity and interaction between different pathologies we will likely not be able, at least not in the near future, to parse out state and progression of each of the individual pathologies.

**Walter Maetzler, University of Tuebingen, Germany**

**Everyday-relevant mobility biomarker: Impossible? Possible? Already available?**

An ideal biomarker also has a high ecological validity; i.e. it measures everyday-relevant features which, ultimately, improve the quality of life of the affected individual. This is a particularly important aspect for the assessment of changes in chronic diseases such as neurodegenerative movement disorders. This talk will provide information about definition and relevance of the term "ecological validity". Moreover, the talk will provide an overview of potential quantitative mobility markers that have already been associated with everyday life aspects and quality of life in the elderly, and individuals with a neurodegenerative disorder, in particular with Parkinson's disease. I will focus on recent studies that describe the use of small, (relatively) inexpensive and unobtrusive wearable sensors, which measure continuous movement measurement in the home environment of patients to assess disease-relevant problems / changes in the everyday environment. There is hope that data obtained with these techniques can in particular add to the development of high quality progression (bio)markers. Options to improve the quality of these markers will be discussed.

**S. 3. Monday June 30, 12:30 – 14:30**

**Advanced methods to identify balance control mechanisms in stance and gait**
**Discussant: Herman van der Kooij, University of Twente, The Netherlands**

**Herman van der Kooij, University of Twente, The Netherlands**

**Identification of asymmetries in balance control in neurological patients and age dependent changes in balance control in elderly**

By applying whole body perturbations and force fields, balance control mechanisms can be manipulated and simultaneously identified. We have developed techniques to measure response behavior and response variability of multi-segmental balance control. These techniques have been applied to identify asymmetries in stroke survivors and PD patients that were not (correctly) detected by conventional posturography techniques. In PD patients, deficit, excessive impairments, and compensatory mechanisms were detected and quantified at the ankle and hip in each leg. In elderly these techniques were able to quantify differences in balance control mechanisms between young and healthy elderly, and between healthy elderly and elderly with balance control problems, polyneuropathy or cataract.

**Thomas Mergner, Neurological University Clinic, Germany**

**Sensor fusion based postural control model and its generalization for use in a modular control architecture of a multiple degrees of freedom body.**

Postural responses to unforeseen external disturbances such as pseudorandom support surface tilts are re-active, meaning primarily sensor driven. These responses lend themselves to system identification and modeling. While the postural responses tend to be stereotype reflexes in the human newborn, they become context dependent during childhood development. Then, they change appropriately with changes in disturbance modality or amplitude and sensor availability (e.g. eyes open vs. closed). These changes can be viewed to result from automatic sensory re-weightings. When trying to model the mechanisms underlying the re-weightings, one faces the problem of many possible solutions. Inspired by human psychophysical studies of vestibular and proprioceptive self-motion perception, a solution based on sensor fusions was developed. The fusions internally reconstruct the four relevant external disturbances having impact on the supporting joints (during biped stance mainly the ankle joints). The disturbances are: support surface rotation and translation as well as field forces such as gravity and contact force such as a pull. The sensory estimates of these disturbances are commanding the proprioceptive servo control of the joints to produce compensatory torque (disturbance estimation and compensation, DEC concept). In an ‘indirect’ system identification approach, human experimental data were compared with model simulations, combining DEC with a priori assumptions about the plant (single inverted pendulum biomechanics). Good correspondence between simulated and human data was found. In a next step, the DEC control was hypothetically generalized as a module for controlling a multi-DOF (degrees of freedom) body. Combining modules, one for each DOF, allows controlling multi-DOF balancing in a surprisingly simple way- complexity rises linearly with the number of DOF. From the modular architecture emerges sensory-driven movement coordination between links. This will be demonstrated for the ankle-hip coordination evoked re-actively by anterior-posterior tilt, pro-actively by voluntary trunk bending, and by a combination of both.

**Tim Kiemel, University of Maryland, USA**

**Using Perturbations to Probe the Neural Control of Walking**

Kinematic and EMG responses to sensory and mechanical perturbations have been widely used to probe the neural control of standing. A perturbation at a single frequency primarily produces a postural response only at the same frequency, but with a scaling of amplitude (described by gain) and a phase shift. The response to a broadband perturbation can be characterized in the frequency domain using a frequency responses function (FRF) describing how gain and phase varies across input frequency. A FRF can be converted to an impulse response function (IRF) in the time domain to describe how posture would respond to a brief perturbation. Here we describe an extension of this approach to probe the neural control of gait. In the time domain, we now use a phase-dependent IRF to characterize the effect of a brief perturbation at any phase of the gait cycle. To compute the phase-dependent IRF, we first characterize the response to a broadband perturbation in the frequency domain using an extension of the FRF called the harmonic transfer function (HTF). The idea behind the HTF is that for a periodic system, a perturbation at input frequency $f$ produces outputs at multiple frequencies $f + kf_0$, where $f_0$ is the gait frequency and $k$ is any integer. The HTF uses gain and phase to describe this input-output mapping for each $k$. We have applied this approach to sagittal-plane dynamics of subjects walking on a treadmill while perturbed by a moving visual scene. Phase-dependent IRFs showed that when the visual scene moved forward, the subjects leaned the trunk forward and moved the center of mass (COM) forward on the treadmill. The COM response was caused not only by the expected increased activation of plantarflexors in late stance, but also by the increased activation of dorsiflexors in early stance.

**Robert J. Peterka, Oregon Health & Science University, Oregon, USA**

**Use of Stimulus-Response Analysis to Identify Mechanisms Contributing to Balance Control During Gait.**

We previously applied stimulus-response analysis to study balance control during stance by (1) using pseudorandom perturbations to evoke sway responses, (2) using spectral analysis of the stimulus-response data to estimate frequency response functions (FRFs) that characterized stance control dynamics, and (3) identifying how sensory reweighting can explain the observed dependence of FRFs on stimulus amplitude [1]. We now demonstrate that similar methods can be applied to identify mechanisms that control medial-lateral (ML) balance during a stepping-in-place (SiP) task. The SiP task serves as a convenient surrogate for the investigation of ML balance control during a walking gait since ML motion of the body center-of-mass (CoM) is similar in SiP and walking. In 6 adult subjects, pseudorandom surface rotations with peak-to-peak amplitudes of 1°, 2°, and 4° evoked ML sway during both eyes-closed stance and SiP. Response measures included ML CoM angle, step width, and step timing (right and left leg “stance times” and “swing times”). FRFs calculated for both SiP and stance tests showed similar dependence on stimulus amplitude suggesting that sensory reweighting contributed to body-orientation control during both SiP and stance. In addition to controlling body orientation, gait requires dynamic balance control to maintain a stable CoM trajectory. We found no evidence that subjects used a mechanism based on step-to-step modulation of lateral foot placement to control dynamic balance. Instead we found that step timing was modulated such that when, for example, the subject was leaning too far rightward, the right-leg stance time was extended to allow for the corrective action of torque due to gravity to be applied over a longer duration. Step-timing adjustments have previously been suggested as a mechanism to control ML dynamic balance in robots [2].

[1] Peterka, *J Neurophysiol*, 88:1097-1118, 2002.
[2] Maufroy et al., *Auton Robot*, 28:331-353, 2010.

**S. 4. Tuesday July 1, 08:30 – 10:00**

## The role and implications of cortical and other supraspinal areas in control of balance and gait
**Chair: Fay Horak, Oregon Health and Science University, USA**

**Klaus Jahn,** Ludwig-Maximilians-University of Munich, Germany

### Task-specific human brain networks for supraspinal control of locomotion, postural balance, and spatial navigation

Over the last 10 years, functional imaging of the human brain during different postural and locomotor tasks convincingly demonstrated that the supraspinal network known in quadrupeds is conserved in humans despite their transition to bipedalism during vertebrate phylogeny. This network includes premotor frontal cortex for task planning and initiation, basal ganglia for motor modulation, the thalamus for sensory modulation, the homologues to the pacemakers for gait pattern and speed regulation in the interfastigial cerebellum and bilateral midbrain tegmentum (cerebellar and mesencephalic locomotor regions; pedunculopontine nucleus), their descending target regions in the pontine reticular formation, and the rhythm generators in the cerebellar vermis and paravermal cerebellar cortex.
We present new data and review the literature showing that differences and similarities on the overlapping networks controlling specific tasks such as stance postural equilibrium and gait. For example, steady state locomotion preferentially involves the brainstem and cerebellar network, whereas goal-directed locomotion requires premotor cortical activity. Postural tasks and slow locomotion use multimodal sensory input (via thalamus and cerebellum). More demanding locomotor tasks (e.g., walking along a narrow beam, avoidance of obstacles) activate a fronto-parietal cortical network. Further, as soon as the task involves spatial orientation aspects, the hippocampal formation and the parietal cortex become active.
Task-specific differences in network activity have great impact on the planning and interpretation of studies on healthy subjects and on patients with gait and balance disorders. We will point out that the methods used (e.g., fMRI, PET, fNIRS, EEG) and the specific paradigm (e.g., steady-state vs. goal-directed locomotion; imagined locomotion vs. overground locomotion vs. treadmill locomotion) should be chosen with care to be able to answer the specific research question.

**Daniel Peterson,** Oregon Health and Science University**,** Oregon, USA

### Supraspinal Locomotor Control in People with Parkinson Disease- Implications for Rehabilitation

Supra spinal brain regions play an important role in human locomotion. Individuals with Parkinson disease (PD) exhibit structural and functional changes in many of the regions associated with locomotion, likely contributing to the locomotor deficits observed in this population. Recent research using a variety of imaging techniques, including task-based functional magnetic resonance imaging (fMRI), resting-state functional connectivity MRI, positron emission tomography (PET), and diffusion tensor imaging (DTI) has begun to elucidate the neural underpinnings of locomotor dysfunction in people with Parkinson disease, identifying a network of regions exhibiting altered activity with respect to healthy adults during gait or gait-like tasks. These differences span much of the brain (motor/pre-motor cortical areas, basal ganglia, cerebellum, brainstem). Several recent studies have focused specifically on freezing of gait, a particularly disturbing and dangerous symptom of PD, noting a number of structure and function neural alterations in those who freeze. For example, alterations in the activity of locomotor structures (e.g. subthalamic nucleus (STN), cerebellum, tegmental brainstem/pedunculopontine nucleus (PPN), striatum), and cortical structures (e.g. insula, supplementary motor area (SMA), pre-SMA) have been noted during gait-like tasks in those who experience freezing. During lower limb motor blocks, thought to be similar to freezing of gait events, the activity in the PPN, globus pallidus, and STN is altered with respect to normal movement. Finally, DTI has shown that the structural connectivity of the PPN with cortical, basal ganglia and cerebellar regions is also altered in freezers and these alterations are related to specific cognitive deficits. Together with resting-state functional connectivity MRI, these data suggest that a complex and distributed group of structures are involved with gait dysfunction and freezing in PD. These findings inform targeted rehabilitation interventions aimed at improving locomotion in those with PD. Further, imaging methods noted above can be used to test whether interventions have effects on neural, as well as behavioral, outcomes. For example, recent reports suggest that freezing of gait may be related to dysfunction in cognitive domains including response inhibition and set-shifting. These findings are supported by imaging data showing altered function in a number of frontal regions related to these cognitive domains. Together, these findings suggest that rehabilitation protocols that incorporate cognitive challenges, specifically response inhibition and set-shifting, may be especially effective at improving freezing of gait in PD.

**Bastian Bloem, University Nijmegen Medical Center, The Netherlands**

**Using motor imagery to study the neural substrates of dynamic balance**

Recently, new opportunities for understanding the cerebral control of human whole-body movements have emerged from the combination of quantitative motor imagery (MI) protocols and fMRI. This approach has been successful in studying static balance control and gait in humans. Surprisingly, dynamic balance control has not yet been investigated, although it is a major function of the postural control system and balance failures often occur while moving. Instability should be thought of as context-specific, where each individual is at risk of falling in different contexts. Indeed, the postural control system includes a number of components underlying the ability to stand, walk and interact safely with the environment. Understanding those components requires examining their individual neural activation patterns under controlled task conditions. Furthermore, gait involves constant interactions between propulsive and dynamic balance components. Such interactions become obvious when gait involves walking on a narrow path or a balance beam. It is therefore relevant to test whether, and how, the neural circuits controlling gait are related to those controlling dynamic postural adjustments. This study aimed at designing a MI protocol that would enable one to isolate the cerebral circuits and connectivity supporting dynamic postural challenges. We explored the spatial relation between cerebral circuits supporting dynamic balance, static balance and gait. By moving backward and forward along the midsaggital plane, participants standing on a balance board aimed a laser dot (mounted on the balance board) at targets of different sizes, placed at different distances. In order to control for subjects engagement in MI during fMRI, we exploited the fact that both physical performance and MI of a given action are influenced by task difficulty according to Fitt's law. Accordingly, the designed postural aiming task manipulated the difficulty of dynamic balance by varying the extent and accuracy of oscillations on a trial-by-trial basis. Afterwards, the participants imagined performing the same dynamic balance task while their BOLD-fMRI responses were recorded. Cerebral responses specific to dynamic balance control were isolated by comparison with a visual imagery (VI) task involving the same sensory input and motor output, but in which participants did not imagine swaying voluntarily. MI and VI durations were differentially influenced by the sway accuracy requirement, indicating that MI of balance is sensitive to the increased motor control necessary to point at a smaller target. Compared to VI, MI of dynamic balance recruited additional cortical and subcortical portions of the motor system, including frontal cortex, basal ganglia, cerebellum and mesencephalic locomotor region, the latter showing increased effective connectivity with the supplementary motor area. The regions involved in MI of dynamic balance were spatially distinct but contiguous to those involved in MI of gait, in a pattern consistent with existing somatotopic maps of the trunk (for balance) and legs (for gait). These findings validate a novel, quantitative approach for studying the neural control of balance in humans. This approach extends previous reports on MI of static stance, and opens the way for studying gait and balance impairments in patients with neurodegenerative disorders, to improve treatment strategies.

**S. 5. Tuesday July 1, 08:30 – 10:00**

**Wearable sensory substitution devices for balance or gait dysfunction: Patient-specific design and optimization**
**Discussant: Conrad Wall**

**John Allum, University Hospital, Basel, Switzerland**
**Modes of vibrotactile and auditory biofeedback of trunk sway for different patient groups**

BACKGROUND: Postural instability is a main feature of several diseases. Providing vibrotactile and auditory feedback of trunk sway has a direct effect on muscle synergies during stance in vestibular loss patients [1], and a positive effect after one training session for those with Parkinson's disease [2]. To achieve these gains a number of feedback modes have been investigated, including lateral or anterior posterior (AP) feedback, dual-tasking and carry-over effects.
METHODS AND RESULTS: Using a headband with 8 equally spaced vibrators and 2 bone-conducting auditory actuators, we first examined whether training with combined vibrotactile and auditory feedback of trunk sway benefits balance control compared to training alone. A benefit of training with biofeedback was present in young adults and to an even greater extent in the elderly [3]. Next we examined whether the benefit differed when feedback was restricted to the AP or lateral direction. For stance, a greater effect of biofeedback was obtained when restricted to the AP direction [4]. For gait, the effects were equal [5]. The benefit of feedback was also tested when dual tasking balance with either motor or mental tasks in the young and elderly [6]. Reductions in sway velocities occurred with feedback for the both tasks in the young but only the motor task in the elderly despite improvement in mental task performance. Finally we established that the carry-over effects for some tasks last about 3 weeks [7] after biofeedback training.
CONCLUSIONS: Bidirectional rather than unidirectional trunk sway information provided by a headband of vibrators is effective in reducing trunk sway in the elderly and patient populations prone to fall. Further research should examine if these effects are

increased after a more intensive or repeated training program and if there are longer term carry-over effects.

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**Patrick Loughlin,** University of Pittsburgh, USA

**Customizing vibrotactile balance feedback**

Falls are the leading cause of serious injury among older adults, resulting in billions of dollars in medical costs and adversely affecting a person's health and quality of life. Accordingly, the development of a balance prosthesis that can provide sensory information that improves balance has become of interest, with clear clinical and economic importance. Owing to the technical challenges and associated risks of an invasive device such as a vestibular implant, the development of a noninvasive balance prosthesis is an area of active research. Different modalities of balance and motion biofeedback have been explored as potential balance prostheses, including auditory, visual, vibrotactile, and mixed modalities. Because it does not interfere with the natural functions of the auditory and visual systems during daily activities, and because many people with vestibular impairments also have hearing impairments and rely heavily on vision for postural cues, several studies have explored the efficacy of vibrotactile feedback (VTF) for improving balance and, to a lesser extent, gait. While these studies have demonstrated improved balance during VTF, most current vibrotactile feedback methods do not take into account the individual's specific balance function, unlike hearing aids and other sensory prosthesis that are tuned to the individual. In this talk, we discuss methods to tailor VTF to the specific user and the potential benefits of doing so. These include subject-specific parameter settings including threshold levels and predictive feedback based on the subject's postural control time delay.

**Kathleen H. Sienko, PhD, University of Michigan, USA**

**Feedback displays for vibrotactile sensory augmentation devices: Spatial resolution and cuing strategies**

Sensory augmentation is a technique for augmenting or replacing compromised sensory information. In the context of sensory-based balance impairments, a sensory augmentation device can provide cues of body motion to supplement an individual's intact sensory systems, using inertial measurement units and intuitive vibrotactile feedback displays. Recognizing the reduced quality of life, increased financial costs, and increased mortality risks associated with balance impairments, an overarching goal of our research has been to design, build, and evaluate a sensory augmentation technology platform for use in clinical and home environments that will supplement current balance rehabilitation best practices while emphasizing co-creation with both the prospective patient population and those administering rehabilitation throughout the design process. We have demonstrated that subjects with vestibular loss and older adults can quickly learn to use vibrotactile sensory augmentation in a research laboratory setting to improve postural stability during quiet and perturbed stance. This presentation summarizes our findings on the effects of the vibrotactile feedback display's spatial resolution on postural sway performance during multi-directional surface perturbations. I will furthermore discuss the implications of non-volitional postural responses to torso-based vibrotactile stimulation on the design of vibrotactile displays for balance-related applications.

**S. 6. Tuesday July 1, 08:30 – 10:00**

**Motor-Cognitive Reserve and Risk: New Concepts and Novel Findings**
**Discussant: Jeffrey M. Hausdorff, Tel Aviv Sourasky Medical Center and Tel Aviv University, Israel**

**Joe Verghese, Albert Einstein College of Medicine, USA**
**Motor Cognitive Risk- MCR**

Many clinical pre-dementia syndromes have been proposed to assess dementia risk, but the need for cognitive testing or biomarkers limits their widespread use. Given the growing global burden of dementia, there is an urgent need to optimize risk assessment and accessibility. The Motoric Cognitive Risk Syndrome (MCR), a newly described pre-dementia syndrome characterized by slow gait and cognitive complaints, can be detected without complex tests. In this presentation, we report global prevalence of MCR in 26,000 participants from 22 studies based in 17 countries. We show that MCR is common in seniors, and a strong risk factor for cognitive decline and dementia. The concept of MCR will be described, the possible utility and assessment of this syndrome and its potential for identifying individuals at risk will be addressed. MCR syndrome is common in older individuals, and this concept can be easily applied in a variety of settings to identify older individuals at high risk of developing cognitive decline or dementia

**Anat Mirelman, Tel Aviv Medical center, Israel**
**Motor Cognitive Interactions as viewed through the window of fNIRS*.***

The relationship between gait and executive function has been previously studied using neuropsychological tests, imaging (e.g., fMRI), and dual task paradigms. These are all indirect methods that assess associations across the domains. Functional near infrared spectroscopy (fNIRS) is a brain imaging technology that detects hemodynamic changes in the prefrontal cortex. The rationale behind fNIRS is that relevant stimuli produce an increase in regional cerebral blood flow due to higher energy demands in "activated" areas resulting in higher blood oxygenation. The technology is portable and can be used to examine brain activity in a direct way during walking. We will present evidence of motor-cognitive interactions during gait from fNIRS studies in healthy adults, patients with PD, and elderly fallers and show how neural activation during gait changes with age, pathology and in response to training , reflecting on plastic changes as response to interventions.

**Brad Manor, Harvard Medical School, USA**
**Modulating brain activity to understand and improve cognitive-motor control**

The observation that performing a cognitive task while walking interferes with locomotor control suggests that the involved tasks compete for shared brain networks and this competition diminishes either one task or both. The notion that dual tasking in general and walking while performing cognitive tasks in particular is dependent upon prefrontal cortex activation suggests that strategies designed to facilitate activation of this brain region may significantly improve performance in one or both tasks. tDCS is one potential strategy to modulate cortical activity that is safe, portable, noninvasive and inexpensive. tDCS modulates cortical activity by inducing a low amplitude current flow between two or more sponge electrodes placed upon the scalp. This current flow changes brain tissue polarity and thus, its excitability. tDCS targeting the prefrontal cortices has proven effective for the treatment of depression and has shown promise in reducing the severity of certain types of chronic pain. Daily sessions of tDCS targeting the sensorimotor cortices may also improve motor outcomes. In this talk, we introduce tDCS as a tool for the study and rehabilitation of locomotion, report initial evidence that tDCS reduces the cognitive dual task costs on walking, and discuss future research applications.

**S. 7. Wednesday July 2, 12:30 – 14:30**

**Can we more objectively measure motor-cognitive functioning to diagnose sports-related concussions?**

**Suggested discussant: Colin Wallace, University of British Columbia, Canada**

**Paul van Donkelaar, University of British Columbia – Okanagan, Canada**
**Neurocognitive deficits following concussion**

Concussion is a challenge to accurately diagnose and manage due to a lack of sufficiently objective biomarkers. Concussions are associated with subjectively experienced physical, cognitive, and psychological symptoms; balance deficits; and cognitive diminishment in many sufferers. These symptoms and problems usually resolve spontaneously over the course of a few days to weeks. Given these challenges, it is difficult to objectively determine the severity of the injury and how to manage it. In the context of contact sports, this can lead to inappropriate return-to-play decisions, leaving athletes vulnerable to subsequent short- and long-term injury if they have not sufficiently recovered. Adults suffering concussion commonly display deficits in maintaining and distributing attention within and between tasks and in the ability to accurately recall items using short-term working memory. In a series of studies over the last decade, we have demonstrated that participants with concussion have marked and long-lasting (up to 2 months) deficits of executive function when performing tasks driven by conflicting cues or requiring task switching. These data imply that executive dysfunction is a common feature underlying some of the behavioural difficulties observed in this patient population. Thus, executive function assessment targeting task-switching holds the promise of providing a sensitive indicator of recovery in the very aspects of neurocognitive functioning that are most compromised due to concussion. In particular, the deficits in these tasks remain after the athlete's performance on clinical assessments has normalized and they have been returned to play.

**Michael E. Cinelli, Wilfrid Laurier University, Canada**
**Magnitude and duration of balance impairments following a concussion**

Concussions are defined as a*, "complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces[1]."* It is estimated that over 300,000 cases of sport-related concussions occur annually in the United States among individuals 15-24 years of age[2]. The number and severity of concussion symptoms vary from athlete to athlete, depending on the biomechanical forces and areas of the brain affected. Although no two concussions are similar in nature, balance impairments are a common cardinal symptom. Research suggests that with 90% of concussions, symptoms resolve within 7 days[3,4], and static stability has been shown to recover within 3–5 days using the Balance Error Scoring System (BESS)[4]. However, we have recently found that balance control of concussed athletes was not fully recovered upon return to play (i.e., 10-48 days post concussion) as indicated by a pronounced increased velocity of Centre of Pressure (COP) in the anterior-posterior (A/P) direction during static balance[5] and greater swing time variability during locomotion[6]. These deficits were evident despite reduction of reported concussion symptoms. We have also demonstrated A/P balance impairment during a gait initiation task, which is a task that challenges the balance control system as it moves from stable static balance to continuously unstable gait. Concussed athletes (~5 days post-concussion) demonstrated significantly greater COP posterior displacement during the loading phase. This increase in posterior COP displacement during the loading phase appears to be a strategy employed to overcome the A/P postural instability to allow for gait initiation to occur. Balance control in the A/P direction is primarily regulated by ankle extensors, which receive input from the descending lateral vestibulospinal tract (VST). We believe that following a concussion, damage to the vestibular system could result in long lasting impairments to the lateral VST and the persistence of poor balance control even in the absence of symptoms.

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**Li-Shan Chou, University of Oregon, USA**
**Examination of the effects of concussion on dynamic balance control during dual-task gait**

Clinicians often rely on clinical symptoms and neuropsychological tests to determine a proper time for a concussed patient to return pre-injury activity. However, executive dysfunction and motor deficits following a concussion have been found, in adults and adolescents, to require greater recovery time than commonly assessed neuropsychological variables. This suggests that more extensive and complete testing following concussion is needed to make appropriate decisions on return to vigorous activity. Including a cognitive task during walking allows for simultaneous assessment of motor and cognitive performance. Individuals with concussion were reported to adopt a more conservative gait pattern or continue to display altered walking performance during dual-task conditions despite undetectable differences on measurements of symptoms and neuropsychological tests. Our prospective and longitudinal studies further examined how dynamic balance control during dual-task walking is affected by concussion within an acute post-injury interval (<72 hrs) and over the subsequent two months. The center of mass (COM) medial/lateral (M/L) displacement and peak M/L velocity were significantly greater in concussed subjects compared with control subjects during dual-task walking. These data suggest that concussion affects the ability to control body posture and momentum during gait up to two months following injury. Dual-task cost for the walking speed, peak anterior COM velocity and COM M/L displacement for concussed subjects were also found to be greater than control subjects across the two month testing period. This could indicate a disruption of the integration between motor or cognitive function during walking. Taken these findings together, if the ability to walk or maintain balance is inordinately affected by the implementation of a single additional task, individuals suffering from concussion may be less able to avoid hazards during normal activities and thus susceptible to further injury for a prolonged period of time during the post-concussion period.

**Bradford J. McFadyen, Université Laval, Canada**
**Behavioural markers for sensitive, ecologically valid detection of motor-cognitive functional alterations following concussions**

Mild Traumatic Brain Injuries (mTBI) are still often under- or mis-diagnosed. Residual deficits in motor-cognitive functioning can remain undetected by traditional, isolated, domain specific, clinical testing resulting in many persons with mTBI being returned prematurely to function. While there are many efforts on developing biomarkers and improving imaging, behavioural markers based on ecological, daily activities that naturally combine cognitive and motor functions have the potential to be more sensitive to such residual deficits. They can also provide context specificity to not only guide diagnosis but more specifically aide return to function decisions. Recent evidence from different work, including that of the S. presenters, has shown subtle but clear changes following mTBI in dynamic equilibrium and executive functioning within the context of postural tasks and locomotor mobility. In addition, our work has shown how the manipulation of the complexity of cognitive-motor environmental demands can be exploited to better identify persistent deficits following mTBI. Building on such evidence, this talk will address how behavioural markers might be advanced, particularly through the exploitation of various emerging technology (inertial sensors, motion capture, virtual reality), and integrated into clinical practice to improve clinical decision making.

**S. 8. Wednesday July 2, 12:30 – 14:30**

**Implants and wearable aids for balance and gait dysfunction**

**Discussant: John Allum, University Hospital Basel, Switzerland**

**Conrad Wall, Harvard Medical School and Director of the Jenks Vestibular Diagnostic Lab, Massachusetts Eye and Ear Infirmary, USA**
**Preliminary experiences with the beta test version of a vibrotactile tilt feedback belt**

Background and aim: A beta test version of a wearable sensory augmentation device that uses vibrotactile feedback of body tilt to help people reduce their sway while standing and walking has been developed. A tilt sensor mounted on the small of the back is used to signal the subject about the magnitude and direction of their displacement away from the vertical. Several published studies have shown that subjects can reduce their sway during standing and walking by using this form of vibrotactile feedback. Reduced sway has been correlated with decreased risk of falling. The overall aim is to use the beta version to finalize the production design of a balance belt to be used for balance rehabilitation therapy. Methods: Ten units have been produced and are presently being placed at selected beta test sites. These sites all perform balance rehabilitation therapy. There is a mixture of private clinics and university associated ones. We aim to collect feedback from these sites, and then use this information to inform the production design within a 6 to 9 month timeframe. Results: The focus of our presentation will be to share the lessons learned from this exercise, and the likely changes that need to be made for the production design. Conclusions: The conclusions of our analysis of the information we learn will be based on the data we get from the test sites and will be presented.

**Yuri P. Danilov, Tactile Communication and Neuromudulation Laboratory (TCNL), Biomedical Engineering Department, UW-Madison, USA**
**New approach to neurorehabilitation: cranial nerve noninvasive neuromodulation (CN-NINM technology)**

Introduction: The objective of this study was to investigate the efficacy of cranial nerve non-invasive neuromodulation (CN-NINM) intervention using a portable neurostimulator (PoNSTM) device to treat symptoms of chronic mild to moderate traumatic brain injury (mTBI), especially functional deficits in balance, gait, cognition, and mood. Methods: A single-arm pilot study involving 4 subjects with chronic (5.4 yrs) symptoms of mTBI were tested immediately before and after 2 weeks of CN-NINM intervention on standard functional assessments of balance, gait, cognition, memory, and mood state. Subjects also underwent fMR imaging while observing stereo B/W checkerboards progressing/receding, and rotating in pseudorandom motion to excite the vestibular-ocular reflex circuitry. All subjects had previously completed therapeutic interventions for balance & gait dysfunction, had reached a plateau, and declared clinically disabled. Subjects completed twice-daily training sessions for two weeks (5 days/week). Each session involved 20-minutes each of a maximal-challenge balance, and treadmill-based gait with concurrent CN-NINM stimulation. Results: All subjects exhibited observable improvements in balance and gait, cognitive function, memory, attention and mood. Dynamic Gait Index: a test of 8 facets of gait including modulating speed, turning the head during gait, stepping around and over obstacles, and ability to climb stairs. Subjects exhibited improvements in scores of 13.5, 14, 10, and 21.5 points, respectively on a 24-point scale. A 3-point change is considered clinically and statistically significant. NeuroComTM Computerized Dynamic Posturography Sensory Organization Test (SOT)

– standing balance performed under six sensory conditions to quantitatively evaluate the relative use of visual, vestibular and proprioceptive inputs in dynamic balance control. Subjects exhibited improvements in scores of 62, 10, 22, and 47 points, respectively on an age & height normalized scale. A 10-point change is considered clinically and statistically significant. Additionally, TBI Subjects C & D were tested for changes in cognitive function, memory, attention and mood. Their scores on the Brief Repeatable Battery of Neuropsychological Tests (BRBNT) exhibited improvements in all 7 categories of test for declarative and spatial memory, attention, arithmetic capacity, and mood. We observed that twice daily application of superficial electrical stimulation to two major cranial nerves (lingual branch of the trigeminal nerve and lingual branch of the facial nerve), innervating the anterior 2/3rd of the dorsal surface human tongue induces increased activity in the brainstem. The specific regions exhibiting increase metabolic activity in the dorsal pons varolli, superior medulla, and ventrolateral cerebellum all structures intimately involved in balance, gait, head and eye-movement control. We postulate that systematic application of CN-NINM induces processes of neuroplasticity that leads to improved and sustained functional behavior regulated by these structures. Conclusions: Prolonged activation produces sustained increased neural activity in at least the sensory and spinal nuclei of trigeminal nuclei complex, and the caudal part of the nucleus tractus solitarius where both stimulated nerves have direct projections. It may also increase the receptivity of multiple neural circuitries and/or affect internal mechanisms of homeostatic regulation, according to our contemporary concept of synaptic plasticity.

**Richard F. Lewis, Harvard Medical School, USA**

**Vestibular prosthesis tested in non-human primates**

Background and Aims: We have investigated the vestibulo-ocular reflex (VOR), tilt perception, and postural stability in rhesus monkeys in the normal state, after bilateral vestibular ablation (BVH state), and in the BVH state aided by an invasive canal prosthesis. Methods: The prosthesis senses angular head velocity and provides this information to the brain by electrically stimulating canal ampullary nerves. Results: We found that the angular VOR is improved by prosthetic stimulation, and that the perception of head orientation in space is affected by electrical stimulation. Postural stability in the BVH monkey during quiet stance was not affected by electrical stimulation, but trunk motion during head turns was reduced by prosthetic stimulation.

Conclusions: These results indicate that an invasive canal prosthesis can provide angular head velocity information to the brain that improves the VOR, the perception of head orientation in space, and postural stability associated with head motion. Further work is needed, both in human subjects and non-human primates, to determine more definitively the benefit of invasive canal prosthetics in subjects with severe vestibular deficits.

**Dietmar Basta, University of Berlin, Charité Medical School, Germany**

**Efficacy of vibrotactile vestibular neurofeedback training based on objective body sway measures in everyday-life conditions**

Background and aim - Vestibular rehabilitation strategies mostly require a long-lasting training, which is finally not often successful. An individualized neuro-feedback training which is based on a body sway analysis in everyday-life conditions seems to be a more promising approach. Hence, the present study was aimed at investigating the efficacy of individualized vibrotactile neuro-feedback training for vestibular rehabilitation in a double-blind, placebo-controlled multicenter study. Methods - One hundred thirty two patients who experience one of the following balance disorders for more than 12 months were included in the study: canal paresis, otolith disorder, Parkinson's disease, and presbyvertigo. Vibrotactile neurofeedback training was performed daily (15 min) over 2 weeks with the Vertiguard-system in those 6 tasks of the Standard Balance Deficit Test (14 everyday-life conditions) with the most prominent deviations from the normative values. The Vertiguard-system measured the velocity during performing the tasks close to the center of body mass. The device was connected in the training sessions with 4 vibrotactile stimulators and compared the continuously recorded velocity with individually preset thresholds for the stimulator activation in the specific direction (left/right, forward/backward). Results - A significant reduction in trunk and ankle sway as well as in the subjective symptom scores (DHI/VSS) were observed in the verum group. Such an effect could not be found in any of the outcome parameters of the placebo group. Conclusions - The present findings indicate that the individualized vibrotactile neurofeedback training, as applied in the present study, is a highly efficient method for the reduction of body sway in different balance disorders. Even if the rehabilitation with the Vertiguard-system is effective and shows long lasting effects, the future goal is to develop a prosthesis which provides automatically the correct individual feedback thresholds in the everyday-life of the patient. This would be especially important for the treatment of progressive diseases (e. g. Parkinson's).

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**S. 9. Wednesday July 2, 12:30 – 14:30**

**Exergaming in the elderly for fall risk reduction and prevention: Challenges and future directions**
**Chair: Nina Skjaeret, Norwegian University of Science and Technology, Norway**
**Discussant: Stephen Lord, University New South Wales, Neuroscience Research Australia**

**Claudine Lamoth, University Medical Centre Groningen (UMCG), Center for Human Movement Science Groningen, The Netherlands.**
**Development of an interactive gameplay tool for balance training of elderly**

Fall related injuries are responsible for disability, physical dysfunction and loss of independence among older adults. Primary causes of falling are postural instabilities during daily activities. Developing a tool to train balance is therefore of great importance. The project "Exergaming for balance training of elderly" of SPRINT/UMCG, aims to develop a gameplay system for balance training of seniors at home and integrates game characteristics that brings added value over conventional balance training [1]. First, an important feature of exergames is that it takes the player's attention away from the motor task and focuses on achieving game performance goals, while simultaneously balance is practiced. This external attention focus results in greater automaticity of postural control [2]. Second, algorithms will be developed to quantify postural control during game play to adapt the game to individual capabilities of the user, and to monitor progression over days/weeks/months [3]. Third, effective balance training programs include high doses and challenging variable exercises, with a large number of repetitions [4]. This can be accomplished by varying game-context and performance requirements. Finally, game systems can provide feedback at different time scales: to the gamer during game play, on activity frequency and duration and users can compare their current performance to past performances, and to other users. These factors might also increase adherence to balance training, because it enhances motivation and enjoyment of exercising. We adopt a multidisciplinary approach in which game designers/programmers, human movement scientists, rehabilitation scientists and biomedical engineers work together. Moreover, the project builds on a user-centered design approach to ensure that the game system will fit the user's demands.

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**Daniel Schoene, Neuroscience Research Australia**
**Stepping exergames and the risk of falling in older people**

Stepping exergames such as Dance Dance Revolution emerged in the 1980's and are still popular among young people today. Recently, similar stepping games that use pressure sensors under the feet have been used by researchers to explore their potential in reducing the fall-risk and improving functional outcomes in older people. Besides the potential effects on health-related outcomes the accessible low-cost technology, use as home-based interventions and increased motivation as well as intention-building aspects of exergames offer significant advantages over traditionally delivered exercise programs. However, evidence in samples of older people is scarce. In principle, stimuli emerge on a display screen providing a task to which the player has to react with a step response, therefore demanding perceptual, cognitive and motor capacities. Findings of multiple studies have demonstrated that specific functions from those domains can discriminate fallers from non-fallers. Thus, stepping exergames may provide a means of targeting risk factors in real-life scenarios. So far no studies have been powered to investigate the effect of an exergame intervention on fall rates. Stepping exergames are safe and appear to be feasible as an in-home intervention in healthy samples and under supervision in frailer older adults. There is limited and in parts inconsistent evidence that exergame participation can result in improvements in clinical outcome measures such as balance, fear of falling and cognition. Our group has developed stepping tasks that are not just a modified version of dance games but other tasks that focus on specific cognitive functions in combination with stepping, such as a Trail Stepping task and a step version of Tetris. Preliminary results demonstrate the utility and feasibility in assessing and reducing fall-risk. A randomized controlled trial is currently underway and the results regarding changes in cognitive and motor functional performance from this and other studies will be presented.

**Alan Bourke, Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland**

**Challenges of developing an inertial sensor based stepping exergame for the elderly**

It has recently been shown that exergaming can increase exercise adherence and uptake in an elderly population thus reducing the risk of falling. Therefore, the motivation to develop virtual reality based exercise interventions is warranted. However, in order to develop such an intervention certain criteria need to be considered. The minimum requirement for these exergames is that they should be fun and engaging as well as challenging and safe. We present the design elements and challenges involved in bringing a virtual reality based stepping exercise intervention from concept through to reality. This exergame, developed in the framework of the EU-funded FARSEEING project, allows the user to interact with a three dimensional graphical environment, which is projected in their field of vision. Direction is given via visual feedback to the user on which target to virtually contact with a virtual representation of their feet in the form of an avatar. The user's feet movements are tracked using inertial sensors which measure true displacement of the feet in real-time which is used as input to the game engine. In order to develop such an exergame a number of technical computational and algorithmic challenges needed to be addressed. We present the technical requirements for the system, including the interface, processing unit, sensors and communication. We also cover the animation, safety and intervention design including the taxonomy and the implemented system for the final virtual reality exergame. We cover in detail the challenges faced when performing real-time foot trajectory measurement and how these were overcome in terms of real-time implementation, developed algorithms for step detection and trajectory measurement where finally we conclude with a presentation of the developed exergame.

**Brook Galna, Newcastle University, UK**

**Designing exercise based computer games for people with Parkinson's disease**

Parkinson's disease (PD) is a multi-system neurodegenerative disorder that impairs postural control and mobility, causing falls and reduced levels of physical activity. The overall impact of PD on quality of life is marked. Exercise is effective in improving gait, balance and mobility in PD but professional resources are limited and alternative approaches to provision of exercise and rehabilitation programmes need to be found. An alternative is the use of exercise-based computer games (exergames) such as those played with Nintendo Wii and Microsoft Kinect. However, commercial games are not designed with specific rehabilitation strategies in mind, nor are they designed to accommodate the various motor and non-motor symptoms associated with PD such as tremor, dyskinesia or cognitive dysfunction. This poses challenges to their application and utility. Key features of exercise programs in PD are considered to include: practice of complex tasks (total body movement rather than exercising a single joint); use of sensory input for augmented feedback (e.g. sound and vision) regarding performance; graduated and goal-directed activity; intensity and frequency of practice. In response to these needs, we developed a stepping based exergame using the Microsoft Kinect to rehabilitate balance in people with PD (PD-Kinect). The aims of this presentation will be to i) summarize the emerging literature on exergaming for people with PD; and ii) describe our team's experience in designing an exergame specifically for people with PD. Particular emphasis will be placed on the iterative design process we adopted involving people with PD as well as the feedback we obtained from people with PD who played the game.

**S. 10. Thursday July 3, 15:00 – 17:00**

## Proactive and Reactive Adaptations to Slips and Trips: Implications for Fall-Risk Assessment and Rehabilitation

**Shirley Rietdyk, Purdue University, USA**

### Failures of Proactive Gait Adaptations: Individual and Environmental Characteristics that Result in Failure to Cross a Visible, Stationary Obstacle

Most environmental challenges encountered in daily life are visible from a distance, such as stairs, ramps, and obstacles. The first line of defense to prevent a fall from these challenges is the proactive gait changes made to avoid or accommodate the environment. However, even when an obstacle is perceived in the environment, and proactive gait adaptations were made, failure can still occur due to inadequate adaptations. For example, a person perceives a staircase, elevates the limb to clear the stair, but trips on the stair. These failures also occur in the lab, and most subjects fail at least once when enough trials are observed. Examination of these proactive failures informs fall risk from a new perspective. We have observed that young and older adults have similar obstacle contact rates in a lab setting; so age does not increase the likelihood of obstacle contact in a normally lit environment with a high contrast obstacle. However, older adults are more likely to contact with the lead limb; since lead limb contacts are more difficult to recover from, older adults are less likely to recover and therefore are more likely to become injured. Changes in foot clearance over time appear to indicate that both young and older subjects have an inaccurate perception of obstacle height or that the visuomotor transformation is compromised during control of lead and trail limb elevation. Further, we have begun to systematically manipulate environmental characteristics to empirically determine their direct impact on failures. The identification of antecedents of trips may lead to development of improved interventions, including environmental remediation and proactive obstacle avoidance training.

**Mirjam Pijnappels, VU University Amsterdam, the Netherlands**

### Limitations and possibilities in the reactive recovery responses after tripping in older adults

Tripping over an obstacle induces a forward body rotation. Reactive responses need to be fast and powerful in order to restrain this forward angular momentum and to prevent falling. These reactions might be affected by age-related neuromuscular decline and inadequate responses can lead to falls. The first question that will be addressed is why reactive balance recovery responses after tripping are less successful in older adults than in young adults. We tripped young and healthy older adults repeatedly in our experimental setup over suddenly appearing obstacles while walking overground at preferred walking speed. While young adults responded with a single step, older adults were more likely to take multiple shorter steps after recovery foot landing. Our results showed that the support limb plays an important role in balance recovery by generating the appropriate joint moments during push-off, necessary to restrain the forward angular momentum before landing of the recovery foot. Older adults showed similar onsets of muscle activity and joint moments as young adults, but insufficient reduction of the angular rotation during push-off and poorer placement of the recovery limb. The less adequate body orientation at recovery foot landing appeared not to be due to inadequate arm movements, but rather to lower rates of moment generation in all joints and a lower peak ankle moment in the support limb. The second question then to be addressed is whether such inadequate lower limb responses can be improved by training. We found that older trainers who increased their muscle strength capacities over a 16-week resistance training period improved their tripping responses by 49%. Interestingly, controls that did not change in their strength capacities also improved their tripping responses by 20%, indicating that motor skill learning can have beneficial effects on balance recovery. These promising results are further underlined by recent findings that young adults can adjust their ongoing reactive recovery response after tripping. It seems therefore that adjustments and improvements of reactive balance recovery responses are possible, which might be helpful to prevent falls.

**Tanvi Bhatt, University of Illinois at Chicago, USA**

**Fall prognosis and prevention: Perturbation-based assessment, adaptation and generalization in the young, old and neurologically impaired**

Despite the commonality of falls within the community-dwelling aging and disabled population, little is known about their mechanism or their contributing factors, with limited tools assessing this crucial aspect. Further, there are limited evidence-based treatment approaches for fall reduction in these populations. Accurate assessment measures can form the baseline for development of appropriate and effective interventions in order to prevent falls and improve quality of life and community participation. Perturbation-based assessment and treatment is an emerging field that holds potential to address the epidemic of falls. Based on previous theoretical and empirical evidence we explored the feasibility of applying laboratory-induced falls for assessment of real-life falls in community-dwelling older adults and people with stroke. Further we examined the validity of different routine (performance-based) clinical balance tests in predicting an imminent fall in these groups. Both traditional qualitative and quantitative balance assessments were obtained. *Immediate fall risk* was assessed by exposing subjects to an unannounced, novel "real-life-like" slip induced with a low friction moveable platform. We observed that individuals experiencing a fall on the laboratory slip-test had significantly lower scores on the functional status measures compared to those who recovered. Further the measures of stability and limb support were more sensitive in predicting falls than the functional status measures. Next we examined the adaptation effects induced by such repeated laboratory perturbations and the ability to generalize their effects to different contexts. Healthy subjects were exposed to repeated moveable platform slip perturbations induced under their right limb and were subsequently exposed to slips under the non-trained limb, non-trained surface (oil contaminated vinyl floor) and non-trained perturbation (trips). We observed that the perturbation-training induced adaptations could be significantly generalized between limbs, surfaces and contexts, resulting in reduced fall outcomes on exposure to these novel, non-training environments. Lastly to address the role of neural substrates underlying such adaptations, we asked if the adaptive effects observed within a healthy nervous system would be impacted by a neurological insult such as a stroke. Results indicated that people with hemi-paretic chronic stroke could adapt their center-of-mass stability and compensatory stepping responses similar to healthy older adults for preventing fall-risk. Given these positive results, perturbation-based assessment and training could be used as an adjunct to current rehabilitation paradigms to target fall-prevention.

**Yi-Chung (Clive) Pai, University of Illinois at Chicago, USA**

**Long-Lasting Human Motor Memory: Perturbation Training against Falls Among Community-Dwelling Older Adults**

Letting older adults slip and fall seems counterintuitive. However, due to the vital functional plasticity of the human motor system, allowing older adults to slip and fall in a safely controlled environment may in fact may help them develop skills that subsequently reduce likelihood of falls in uncontrolled and dangerous everyday living situations. Perturbation-training is one such emerging paradigm known to induce shorter-term falls reduction in healthy young as well as older adults. Its longer-term benefits are not fully understood, however. The purpose of this study was to determine the length of time and to what degree older adults could retain their fall-resisting skills acquired from a single perturbation training session. In this conditional three-stage, sequential, pre-post-retest design, subjects underwent the initial training session at the beginning of each stage in precisely the same manner as their cohorts of other stages, and returned to participate in a retest only once at the end of that stage just as did the other cohorts. Seventy-three community-dwelling older adults (≥ 65 years) received perturbation training consisting of 24 slips in the initial session. Outcome measurements, taken upon the first (novel) and the 24th (final) slip of the initial session and the retest slip, included fall-or-no-fall, and stability (quantified by the shortest distance form relative motion state of the center-of-mass and the base-of-support to the limits of stability) at instants prior to (proactive) and after (reactive) the onset of the slip. Whether or not the participants successfully retained their training in the retest of a given stage would then determine the length of time for the retest in the next stage. If the participants in Stage I exhibited significant retention during their 6-month retest, the second cohort of subjects (Stage II) would then retest nine months after their initial training. Alternatively, if six-month retention was not observed in Stage I, Stage II participants would retest three months after their initial session. The outcomes observed for Stage I and Stage II would then dictate whether the retest for the cohort in Stage III would be either at one-and-a-half, four-and-a-half, seven-and-a-half, or at 12 months after their initial session. We found that the training boosted subjects' resistance against falls with a significant reduction from 42.5% falls on the first slip to 0% on the 24th slip. Rate of falls remained low in 6-month (0%), 9-month (8.7%) and 12-month laboratory retest (11.5%); with no significant difference between the three time intervals. Such reduction of falls and its retention were due to the significant training-induced improvement in the proactive and reactive control of stability. The method applied in the present study eliminated any bias resulted from the training effect resulting from multiple retest and provided a high temporal resolution of training retention as fine as 1.5 months. Although it is very time consuming, it offers maximal flexibility. The findings thus enabled us to demonstrate the feasibility of a single session of perturbation training to "inoculate" older adults and to reduce their annual risk of falls.

**S. 11. Thursday July 3, 15:00 – 17:00**

**Multi-person entrainment in gait and posture: theories and approaches**

**Chair: Mark T. Elliott, University of Birmingham, UK**

**Vassilia Hatzitaki, Aristotle University of Thessaloniki, Greece**

**Interpersonal entrainment in dancers: Contrasting timing and haptic cues**

We examined the nature of interpersonal synchrony mediated by light fingertip touch when individuals rhythmically sway side by side at their own pace, same or different externally imposed (metronome) tempos. Three types of couples participated in two experiments; expert couples, consisting of individuals with at least 8 years systematic practice in traditional Greek dance; novice couples, consisting of individuals with no prior experience in dance and mixed couples, consisting of one expert dancer and one novice partner. Analysis of the centre of pressure signals in the frequency domain revealed that fingertip touch evoked interpersonal synchronization during self-paced sway. During metronome paced sway (0.25 Hz) only expert dancers further increased synchronization suggesting a more efficient integration of tactile and timing cues[1]. In a subsequent experiment, we asked whether dancers are able to suppress the spontaneous tendency towards entrainment when the two partners sway at different tempos (one at 0.25Hz, the other at 0.35Hz). Haptic touch evoked interpersonal entrainment only in mixed couples whereas touch interference was weaker in novices and absent in experts. Interestingly, in mixed couples, the expert dancer consistently led his/her novice partner[2]. All together, these results suggest that light fingertip touch evokes spontaneous interpersonal entrainment. The touch effect is stronger when this is provided by an expert in movement timing (i.e. dancer) due to more reliable cues about sway sensed at the fingertip. Suppression of the spontaneous interpersonal entrainment in expert dancers suggests that explicit training in movement timing can modulate the self-organized properties of inter-personal entrainment.

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**Jeffrey M. Hausdorff, Tel Aviv Sourasky Medical Center and Tel Aviv University, Israel**

**Modality-specific communication enabling gait synchronization during over-ground, side-by-side walking**

An attentive observer will notice that unintentional synchronization of gait between two human walkers occurs fairly frequently. The frequency with which this occurs and the mechanisms underlying this phase-locking of rhythms and the gait pattern have only recently begun to be studied. We examined the potential sensory mechanisms that contribute to the gait synchronization that occurs when two people match their rhythms and gait patterns under natural walking conditions, using quantified measurements. Gender and height matched pairs walked a 70 meter path under five conditions that manipulated the available sensory feedback. The modalities studied were visual, auditory, and tactile. Each modality was investigated in isolation and compared to walking when sensory feedback was withheld and when all three modalities were available. Movement data was recorded using two trunk-mounted triaxial accelerometers. Offline, a gait synchronization index (GSI) was calculated from the vertical component of the acceleration signals, quantifying the synchronization of the gait rhythms on a scale of 0-1 using the phase-synchronization method with 0 indicating no synchrony and 1 indicating maximum synchrony. Overall, 36% of the trials exhibited synchrony. Tactile and auditory feedback showed the greatest ability to synchronize, while visual was the least effective. The results show that gait synchronization during natural walking is not merely anecdotal but is a repeatable phenomenon that is quantifiable and is related to the available sensory feedback modalities. In follow-up work, we investigated the role of attention to determine the degree to which automaticity regulates the synchronization among pairs. Further work is needed to more fully identify the mechanisms that govern the synchronization of walking rhythms, to understand how and why some couples are more likely to walk in synchrony, compared to other, and to characterize the dependence on a variety of known and as yet unidentified sensory communication modalities.

**Mark T. Elliott, University of Birmingham, Edgbaston, UK.**

**The entrainment of gait when walking in group formations**

When walking side-by-side, two individuals will tend to fall into step with each other and walk in synchrony[1,2]. This has been observed in both treadmill walking[3] and natural overground walking[2]. The level of synchrony between walking couples is modulated by the sensory information available within different modalities, with tactile cues (e.g. hand-holding) resulting in the greatest levels of entrainment between couples[1–3]. Currently, while gait entrainment has been studied under dyadic conditions, it is unclear whether entrainment occurs within larger groups and under what conditions. In my presentation, which forms part of the S. on Multi-person entrainment in gait and posture, I describe the entrainment of gait between individuals walking in a group of four. In addition, I investigate how entrainment is affected by walking under different conditions, including when holding a conversation within the group (compared to silence) and walking in a rush (compared to relaxed). Groups were gender matched and instructed to walk either in a 2x2 formation or as a single row of four. The experiments took place in a 17m x 12m open area laboratory with a 16 camera Vicon motion capture system (capture volume ~10m x 5m). Participants completed 6 lengths of the lab for each trial while wearing a full Plug-in Gait marker set. Participants were instructed on the formation and walking speed along with a topic of conversation in the talking conditions. I will report the results in terms of the kinematics of movements of each group member under the conditions tested and also the degree of synchrony achieved within the group as a whole and between pairs. I will discuss how results of these kinds of experiments can inform modelling of human-structure interaction research and the prediction of building structural vibration.

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**Andreas Daffertshofer[1] & Vivien Marmelat[2]**
**[1]MOVE Research Institute Amsterdam, VU University Amsterdam, The Netherlands**
**[2]Movement to Health (M2H), Montpellier-1 University, EuroMov, France**
**Long-range correlations in temporal sequences – designing auditory cues for locomotion**

The temporal correlation structure of consecutive events contains valuable information about its generating process. We focus on power law distributions in systems that are considered generic markers of healthy and adaptive performance. (Persistent) long-range correlations change with task and environmental constraints. Temporal correlation structures of motor events are linked to pathologies like Huntington's and Parkinson's disease. With respect to the latter, auditory cueing is often assumed beneficial for gait stability. Stride length, cadence, and speed can increase, whereas inter-stride variability and occurrence of freezing decrease when patients are 'paced' by a metronome. However, isochronous auditory cues alter the typical dynamics of healthy gait: persistent long-range correlations in stride intervals of self-paced gait can switch to anti-persistent correlations. Hence, we discuss whether a train of auditory cues with more fractal-like correlation structure can yield a more consistent and predictable adaptation of motor performance. This is particularly interesting in the context of so-called 'strong anticipation' that facilitates subjects to synchronize with a metronome even if the sequence is random. We present experimental findings that may form help understanding effects of (correlations in) auditory cueing on gait, which can open new opportunities for optimizing cueing protocols in the presence of neurodegenerative pathologies.

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**S. 12. Thursday July 3, 15:00 – 17:00**
**The Interplay Between Cognition and Mobility: Cutting-Edge Neuroimaging Insights**
**Designated Discussant: Professor Stephen Lord, University New South Wales, Neuroscience Research Australia**

**Kim Delbaere, University New South Wales, Neuroscience Research Australia**
**White Matter Integrity, Cognitive Function, and Mobility**

Mobility requires the structural and functional integrity of neural networks to process sensorimotor input. White matter (WM) integrity is essential for fast and efficient operation of the neural networks. Reduced WM integrity is associated with increased fall risk, including impaired executive functioning, impaired balance, slow gait, and falls. Specifically, subcortical infarcts (SI) and white matter hyperintensities (WMH) are associated with an increased risk of multiple falls. Both SI and WMH are commonly found in frontal and subcortical areas and could disrupt the integrity of neural networks including the long descending motor fibers and frontal-subcortical circuits that are important for motor control and cognitive function. In recent years, advances in brain imaging techniques (e.g. diffusion tensor imaging tractography) have allowed us to look at WM integrity directly based on the strength and direction of water diffusivity in WM. Disruption in WM integrity, especially in the corpus callosum and longitudinal association fibres, has been associated to gait and balance impairments. It is assumed reduced WM integrity leads to impairments in functional connectivity of the neural networks. This may have an important effect on processing speed which in turn impacts both motor and cognitive functions. Further, the ability to process and integrate information from sensory, visual and motor domains – essential for balance and gait – are compromised as a result of WM damage. This talk will provide a summary of the growing body of literature linking cerebral white matter disease to deficits in cognitive and physical performance and now, impaired mobility.

**(Co-Presenters): Lindsay Nagamatsu, University of Illinois USA and Chun-Liang Hsu, University of British Columbia, Canada**
**Neural Signature of Impaired Mobility and Their Significance**

Cognitive impairment and impaired mobility are major public health concerns and often coexist – even among functionally independent older adults. The neural basis for this association is currently unclear. We conducted a 12-month observational study to determine the neural correlates of impaired mobility among otherwise healthy community-dwelling older adults aged 70 to 80 years. Specifically, we compared 1) functional brain activation during dual-task performance and 2) functional connectivity (i.e., the temporal coherence of functional brain activation) during rest and a simple finger tapping between fallers (i.e., 2 or more falls in the prior 12 months) and non-fallers (i.e., no falls in the prior 12 months). During functional magnetic resonance imaging (fMRI), participants completed: 1) an event-related cognitive dual-task paradigm and 2) a simple motor tapping task with blocks with rest. Overall, we found that fallers demonstrated reduced hemodynamic response and slower reaction times during dual-task performance compared with non-fallers. Fallers also demonstrated altered between-network functional connectivity. Altered connectivity was observed between the default mode network, fronto-parietal network, and the primary motor sensory network. Thus, a recent history of multiple falls among older adults without a diagnosis of dementia may indicate sub-clinical changes.

**Teresa Liu-Ambrose, PhD, PT, University of British Columbia, Canada**
**Neuroimaging Evidence for "Central Benefit Model" of Exercise in Falls Prevention**

The widely accepted dogma is that improved physical function underlies the effectiveness of exercise interventions in reducing falls risk. However, evidence from our randomized controlled trials suggests that exercise may reduce falls risk via mechanisms other than improved physical function. Specifically, improved cognitive function – specifically, executive functions – and associated functional plasticity may be an important yet under-appreciated mechanism by which the exercise reduces falls risk in older adults. Specifically, we demonstrated that a home-based exercise program of balance and strength reduced falls by 47% among older adults with a significant history of falls -- in the absence of significant improvement in physical function (i.e., balance and muscle strength). Notably, cognitive performance of selective attention and conflict resolution significantly improved in the exercise group compared with the control group.

We also found that improved selective attention and conflict resolution secondary to 12 months of progressive resistance training was associated with improved usual gait speed. Furthermore, exercise may reduce falls risk by slowing down the progression of white matter lesions. Neuroimaging evidence from two randomized controlled trials of exercise will be discussed within the context of the proposed central benefit model (Liu-Ambrose et al., 2013).

**Caterina Rosano, University of Pittsburgh, USA**
**Resilience to Brain Aging: Insights on the Significance of Subclinical Markers of Brain Abnormalities on Cognitive Function and Mobility.**

One hypothesis to explain why older adults remain high functioning late in life is that they have a greater "brain reserve". However, brain reserve has not been objectively quantified, as it has mostly relied on gross measures of whole-brain abnormalities that are largely non-specific manifestation of brain aging. Additionally, the determinants of brain reserve have not been characterized systematically, in relationship to objective measures of brain integrity. We hereby illustrate a method to define resilience to brain aging using objective quantitative measures based on repeated brain magnetic resonance imaging in older adult participants of the Cardiovascular Health Study and Health Aging and Body Composition Study at the Pittsburgh field site. Specifically, we quantified the risk of mortality, dementia, and impaired mobility in older adults in relation to objective quantitative magnetic resonance imaging.