Developing a Human Balance Test System (DETES) in Order to Investigate Control Mechanisms of Human Erect Posture

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Abstract: An originally designed 3-dof (2-dof perturbation platform and 1-dof cabin) human balance testing system (DETES) has been developed for delivering mechanical and perceptual stimuli in a controlled embedding environment in order to investigate sensory-motor control of human erect posture at physiological and/or pathological conditions. The human balance (especially studying vestibular system involved mechanisms) demonstrating complex (nonlinear) dynamical behavior in the context of postural adjustments having ecological roots/meanings (information) is to be tested (by means of quiet and perturbed stance) and analyzed for supporting (differential) diagnosis, monitoring/following the progress of the disease, and creating the new adaptive motor learning protocols for rehabilitation.

Keywords: Human balance testing environment, Mechanical and perceptual stimuli, Complex (ecological) postural behavior, Nonlinear analysis, Information capacity.

1. INTRODUCTION

Balance being a complex function, has been defined as a mean providing postural stability. The aim of postural control is to keep body position in confined space and certain orientation. Balance is maintained by information from the three sensory afferent systems: visual, somatosensory and vestibular; proprioception is implicitly considered. Information from these three systems and corrective reflex motor responses provide to keep the center of gravity in the bearing surface and to maintain the balance [1]. Testing the human balance in different (active and/or passive) sensory environments through mechanical perturbations (known as dynamic posturography [2]) is important to understand the physiological control mechanisms of human erect posture, diagnose and/or rehabilitate the postural or balance clinical problems [3]. Computerized Dynamic Posturography (CDP, developed by L.M. Nashner in 1982, while studying human balance performance on astronauts at NASA [4]) based on the assessment of visual, vestibular and proprioceptive inputs, evaluates the balance system entirely being considered as an important and valuable method for evaluating postural stability [5, 6], where patient stands during the balance test being evaluated for functional balance states similar to daily life experiences. Although CDP helps to the guidance and support in terms of diagnosis, it especially provides benefit in patients' follow-up and rehabilitation [7, 8]. Clinical indications of CDP are complaints about dizziness, patients with known pathology on postural control pathways [9], secondary gain expectation or suspected presence of symptoms due to anxiety and abnormal or suspicious test results from the other balance tests [10].

2. HUMAN BALANCE SYSTEM TESTING ENVIRONMENT

2.1. Mechanical Properties of the Platform and the Cabinet

We have developed a 2-dof tilting human balance testing machine (DETES), which can perform sinusoidal (antero-posterior (A-P) and medio-lateral (M-L)) tilts at 0.05 – 2 Hz frequencies and 1 - 10° of peak amplitude perturbations. The rotation axis of the tilting platform is set to 34.5 cm below than the rotation axis of the ankle. The human balance testing system has also a 1-dof tilting cabinet with the same frequency response characteristics, whose axis of rotation passes through the ankle rotation axis. Figure **1** shows the hard-ware implementation of the system.

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E-ISSN: 2409-3394/16

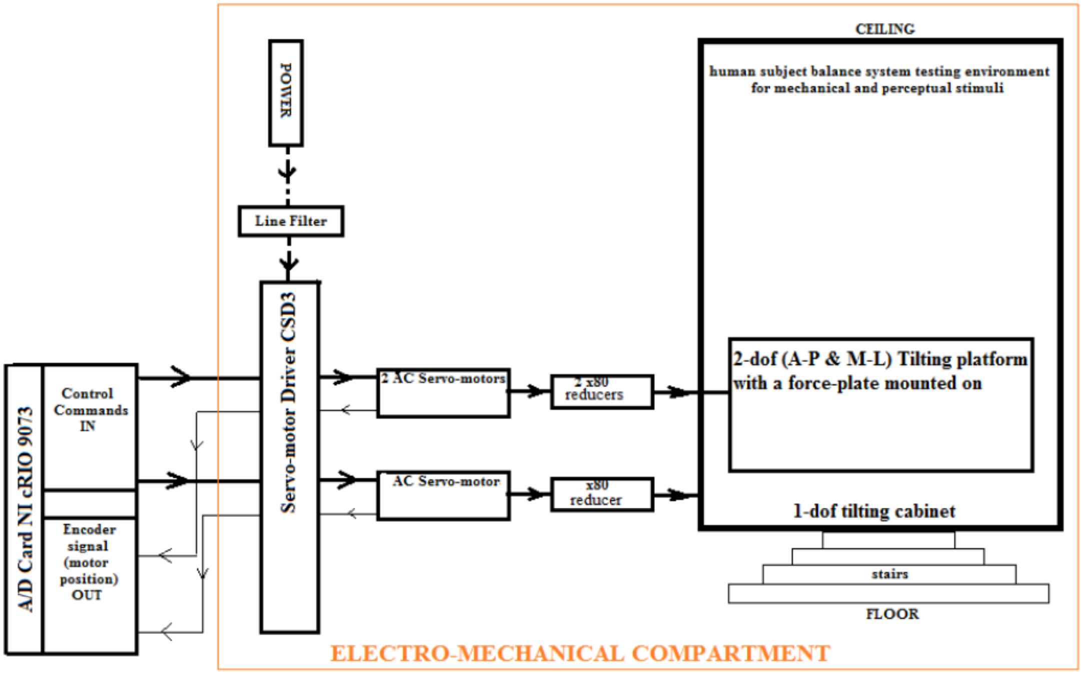

Figure1: Hard-ware implementation of the human balance test system which is composed of electronic (programmable A/D card) and electro-mechanical parts.

AC Servo-motors were Allen-Bradley© OEMax (RD15-A) and the driver CSD3 with the specifications 1.5 kW maxpower, 4.77 Nm max torque capacity, 3000 revolution/minute and the quadrature encoder inside with the characteristics of 2500 pulse/revolution. A reducer of ×80 (reducing the angular velocity by increasing the torque) has been used in-front-of the actuators. An A/D (NI cRIO© 9073) card is implemented to the system for controlling the perturbation platform and collecting data.

2.2. Design Properties and Safety Preventions

The testing cabinet shown at Figure **1** is of cylindrical structure with the diameter being 195 centimeter (cm) and the height is 190 cm. The diameter of the tilting platform is 80 cm where a 40×60 cm force-plate is mounted on. The physical environment (inside the cabinet) is 60 cm higher than the floor where there is a supporting table fixed to the ground in-between the stair-steps for the subjects (patients) to get inside to the testing environment and the tilting platform (equi-levelling stair-steps/cabinet with the tilting platform, see Figure **2**). Inside the cabinet the physical environment is all black and dark through the curtains fixed to the circumference, where the intensity and the frequency of the illumination can be controlled as well as a monitor (40×25**)** is standing ahead of the subjects (at the eye level and approximately 75 cm forward, along the eye-sight), by which visual stimuli can be presented to the subjects. There exists a safety harness fixed to the ceiling where the subjects are dressed with and the holders are fixed to the supporting table, which are parallel to the orientation of the subjects. They are ready to use in an emergency incident throughout the experiments. It is also important to note that the gap is at most 2 mm at its closest position in-between the supporting (fixed) table and the moving (tilt) platform, where it is prevented for any foot-piece (especially fingers) to get into. Additionally there exists an emergency button to stop the running tilt platform by shutting down the power to servo-motor, which is also triggered through the signals coming from proximity sensors.

2.3. Software Implementation, Calibration, Initialization and Control

Six proximity sensors have been used for leveling the tilt platform and the cabinet horizontally. A Labview© code which has been embedded into the cRIO starts with initializing the tilt platform position by using the proximity sensor signal (calibration process), which (from there on) serves as a reference platform position all throughout the data collection period. Next, the code processes the encoder signals (motor position information) inputted to the card in order to control the perturbation platform through a PID controller (the control commands to the actuator are sent to run the servo-motor in speed-mode).

2.4. Experimental Protocol Design

Figure **2** shows the block diagram for designing experiments and running the experimental protocol. The host computer (PC1) showed in Figure **2** controls the flow of the experimental protocol in the physical environment of the set-up. The experimental design has been created in the virtual environment by using State flow 7.6 (Matlab® 2010b, Simulink 7.6) and run through Real-time Windows Target 3.6. There are 2 triggering signals outputted by the host computer (TS1 and TS2) for synchronization of the running Labview code embedded in cRIO 9073 (running the platform) and for the kinematics data collection computer (PC2, through AW Station) through inertial sensors (Xsens, MVN Biomech®) respectively. The signals S1 and S2 seen in Figure **2** are for *servo-on* command, which runs the driver of the servo-motors and through which the actuators are switched off by shutting down the signal (in the case of emergency), while a second signal (by switching off a red-light which is already *on*) is for precaution to the subject to get into the cabinet, warning that the calibration process is over respectively.

2.5. Sensors and Data Collection

There are two basic data collection units (for kinetic and kinematic data) from the subjects during the trials of human balance test at static and/or dynamic conditions. The dynamic conditions are created over either mechanical perturbations and/or perceptual stimuli. Kinetic data (Ground Reaction Forces) is collected by a force-plate (Bertec®, FP4060); *i.e.*, 3 force (F_x, F_y, F_z) and 3 moment (M_x, M_y, M_z) time signals are collected by setting the sampling rate and data collection period of time. F_x and F_y are the friction forces in-between the subject and the tilting platform during the trials, while F_z is the vertical force applied by the subject to the platform (it is the weight of the subject if the trial is quiet stance). M_y and M_x are the two moment signals which are important for computing the center-of-pressure coordinates in the *x*- and *y*-axes respectively (see Figure **3**). Center-of-pressure (*CoP,* an active response) is caused by the projection of the Center-of-Mass (*CM*) of the subject to the horizontal plane (on the force-plate) and is known as the basic balance metric (see Data Analyses and Basic Human Balance Metric Section, Figure **3**). M_z is the twisting moment created by the subject on the force-plate. On the other hand, kinematics data (through tri-axial linear accelerometers and angular velocity sensors, Xsens MVN Biomech®) from the foot, lower extremities, pelvis (CM), upper extremities, trunk, and the head (overall with 15 inertial sensors, in orange at Figures **2** and **3**) are received. By using a 3D-magnetometer, it then becomes possible to compute absolute and relative position (joint angles like ankle, hip, shoulder, head etc) of/from the foot, limbs, trunk and the head in 3-D space [11]. Kinetics and kinematics data are collected and recorded into separate files by different computers, after then the data (stored) analyses are performed off-line.

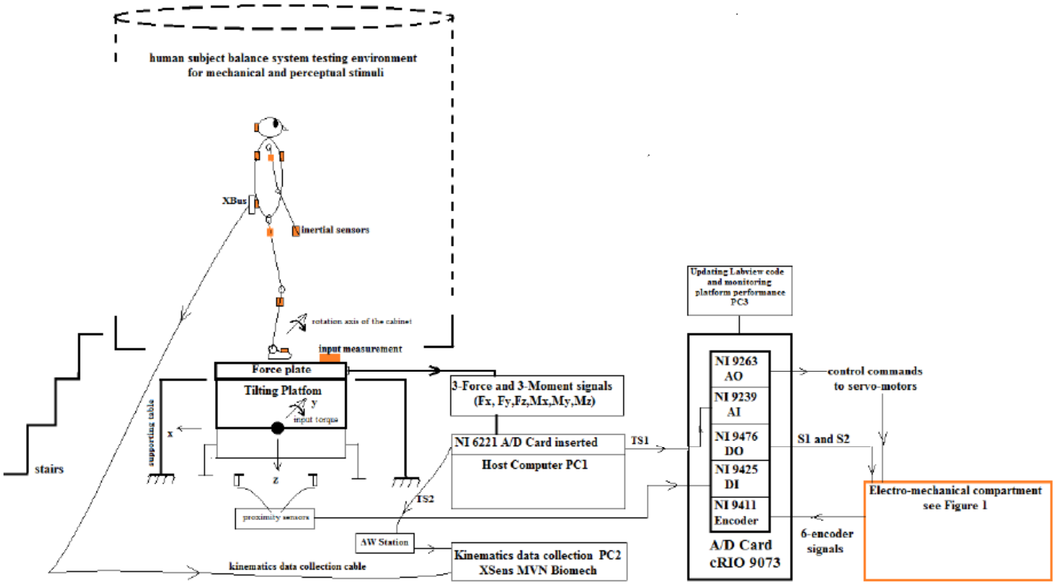

Figure 2: Block diagram of experimental design and data collection set-up. AO, AI, DO, and DI units stand for Analog Output, Analog Input, Digital Output, and Digital Input modules of the A/D card (NI cRIO®) respectively.

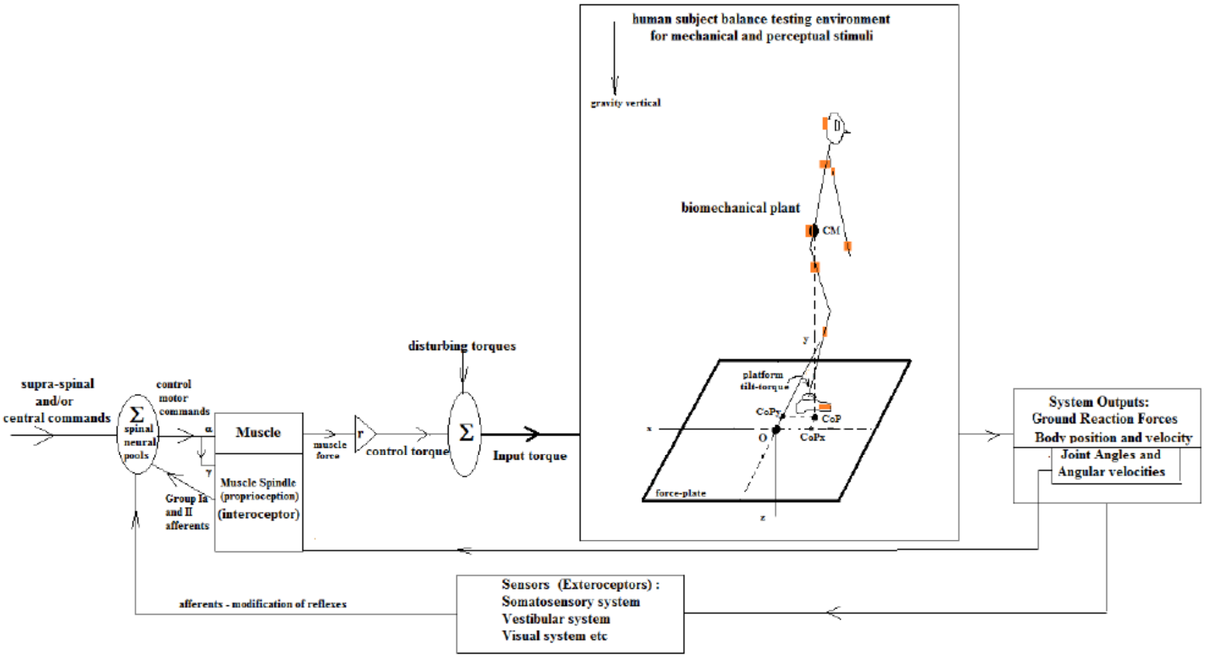

Figure 3: Physiological control diagram of the human neuro-musculo-skeletal system biomechanics where the basic human balance metric; *i.e.*, CoP is shown as the active and speedy response of the human neuro-muscular system to the projecting Center-of-Mass (CM) of the human subject on the horizontal plane [12, 13]. CoP on the horizontal plane is defined by its *x*- ($-M_y / F_z$) and *y*- (M_x / F_z) coordinates.

3. THE ANALYTICAL METHOD

3.1. Data Analyses and Basic Human Balance Metric, CoP

Figure **3** shows the physiological control diagram of the neuro-musculo-skeletal system for human erect posture.

As seen in Figure **3**, Ground Reaction Forces from which *CoP* is estimated and body kinematics are two important outcomes of human biomechanical system created by the muscle forces acting to joints as control torques (*e.g*. ankle, hip, neck, etc) which can be modulated through reflexes triggered by different senses [14]. Also it is important to note that there is a continuous neural stimulation on the spinal neuron pools (modulating signals from upper centers), where spinal/stretch and/or postural reflexes are triggered [15]. Because of the continuously getting updated status of the spinal pools, it is essential to have an estimation about the current state of the spinal neurons and/or muscle activation; *i.e.*, measuring the electro-potentials during muscle activation (as an EMG module to be added to the Human Balance Testing System). As the human postural control is a hierarchically structured complex system with sensory and motor redundancies, the solution to balance problems is not unique; thus in order to understand the control strategies used by the central nervous system, it is not sufficient to measure the kinetic and kinematics of the biomechanical system only, but also necessary to have an estimation about the inner states (*e.g*. muscular electrical activity) of the control system as well [16].

3.2. Case Study (A Healthy Versus Bilateral Vestibular Loss Patient)

Data analyses from *CoP* signal (basic measurement for estimating human balance in quasi static and dynamic conditions, which is derived from kinetic outputs) is performed at time and frequency domains [17]. Figures **4a** and **b** show exemplar CoP_x and CoP_y time signals of an healthy subject collected at quiet stance and their related Fast Fouriér Transformations (FFT, see below paragraph for an explanation/ implication of FFT, Figures **4c** and **d**). Figure **6a** shows both *CoP* signals (CoP_x and CoP_y) at the horizontal plane such that the path traced by *CoP* in time during a balance test presents complex dynamical characteristics (like an individual's signature), where nonlinear dynamical metrics can be computed about the information capacity, dynamical order, and the stability of the individual postural control system [18-20]. Never-the-less path-length (Figures **4a** and **b**), variability of the CoP_x and CoP_y signals and their velocities (variance of the *CoP* displacements and their velocities) give invaluable information about the status (estimation about physiological versus pathological conditions) of the human balance (see Figures **5a** and **b** compared to Figures **4a** and **b**).

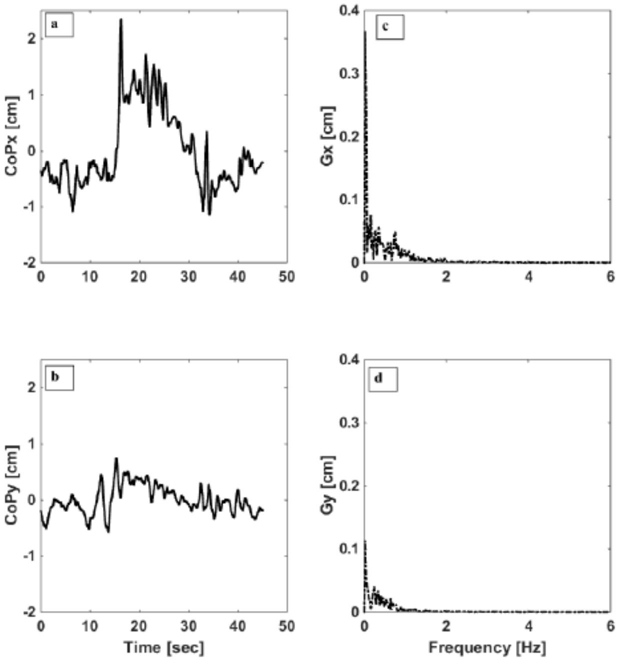

Figure 4: **a** and **b**) CoP_x and CoP_y time signals (quiet stance, eyes open) of a healthy subject on a compliant surface respectively. **c** and **d**) FFT of the time series presented at **a** and **b**.

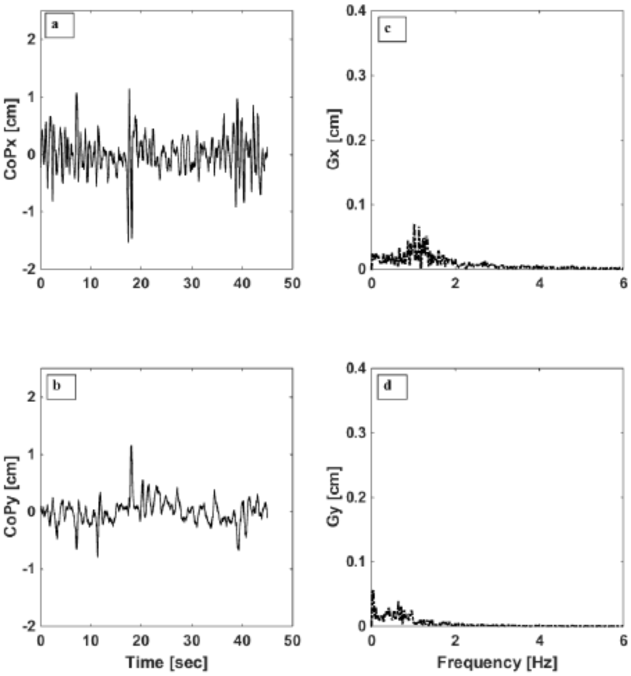

Figure 5: **a** and **b**) CoP_x and CoP_y time signals (quiet stance, eyes open) of a BVL patient on a compliant surface respectively. **c** and **d**) FFT of the time series presented at **a** and **b**.

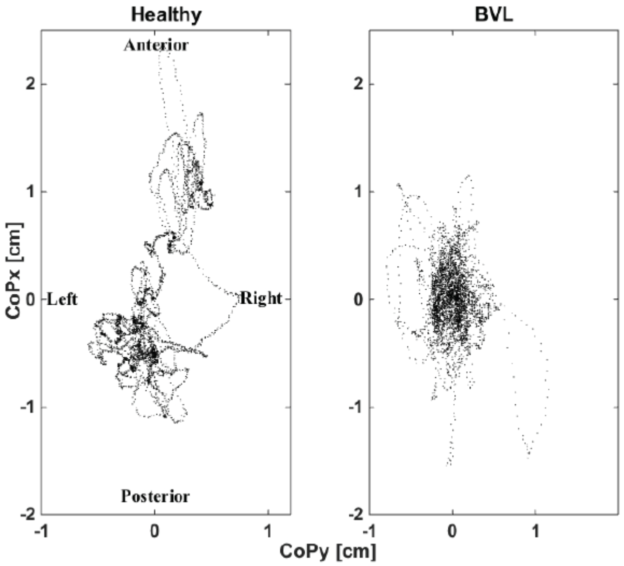

Figure 6: *CoP* sway trajectories on the horizontal plane for a healthy (**a**) and BVL subject (**b**). The time series presented at Figures **4** (**a** and **b**) and **5** (**a** and **b**) have been plotted across each other (time implicit).

On the other hand, Figures **5a** and **b** show CoP_x and CoP_y time signals of a Bilateral Vestibular Loss patient (BVL) and its related FFTs. FFT of a given time series gives information about the power at the particular frequencies embedded in the overall dynamics observed. For example, CoP_x time series shown at Figure **4c** demonstrate power at very low frequencies (below 0.1 Hz), which is a characteristic pattern for a healthy subject's CoP_x signal [21-23]. However, if the FFT pattern of a BVL patient is examined (see Figure **5c**) it is easily observed that magnitude (compare Figures **4c** and **5c**) and the distribution of the power at the frequency spectrum of the CoP_x dynamics is totally different (may be pathognomonic); such that maximum power is no more seen at the very low frequency, rather it has shifted towards somehow higher frequencies (at about 1 Hz, see Figures **5c** and **d**); very likely to be pointing to an instability at the postural balancing adjustments. Furthermore, the distribution of the power at the healthy subject's FFT diagram shoes a maximum at the very low frequency band and a decreasing tendency up to the frequencies at about 1 Hz (see Figures **4c** and **d**), while the FFT pattern of the BVL subject demonstrates more than one maxima without a decreasing tendency. The former pattern (for the healthy subject) might be revealing dynamical characteristics of the complex human erect posture (*searchlike behavior*), while the latter pattern (BVL subject) may be presenting the loss of information about the postural control (deterioration at the *search* *behavior*) with the new emerging frequency bands of instability [24, 25]. Characterization of the postural sway dynamics at the frequency domain is then proceeded by computing Power Spectral Density (PSD) function estimates, area under PSD (is actually the variance of the time series [26]), centroidal and/or median frequency, frequency dispersion (as a measure of power scattering at the spectrum) that has the potential of differential diagnosis in-between the different originated balance problems as well as enlightening the route to the treatment and/or rehabilitation of the disorder.

DISCUSSION

An original human balance testing system for delivering mechanical and perceptual stimuli in order to test the sensory-motor performance of the human balance system has been developed and started being used in the Vestibular Clinics for analysis of the postural control mechanisms in physiological/ pathological conditions aiming to help diagnosis, monitoring/following the progress of the disease, and rehabilitation processes. It is known that human erect postural control is mainly supplied by three senses; somatosensory, vestibular sense, and vision (proprioception is implicitly involved), where any two of these three senses are essential/necessary in order to solve a balance problem [27-29]. Horak *et al*. (1990) showed that postural corrections given to platform disturbance (a translational input) became deteriorated at vestibular loss patients when the somatosensory originated information has been lacking. This is because the vestibular system introduces the sense of verticality to the Central Nervous System (CNS), which is the universal reference for solving any kind of earth-based equilibrium problem [1, 30-32]. In the case of lacking vestibular driven orientation information, the constraints used by CNS in solving the equilibrium problem are strictly restricted: *i.e*., freedom for movement is decreased [33, 34]. So far, we have observed this restricted movement pattern in some of the BVL patients we have tested at their habitual (quiet) stance (as a loss of low frequency band < 0.1 Hz, see Figures **4** and **5 c** and **d**, Figure **6**); whereas when they get disturbed, the postural response appeared has shown high-frequency band characteristics, which we have interpreted as a "*tendency to fall*". We are investigating Unilateral Vestibular Loss patients for the same paradigm (a *search like behavior* at the low frequency band versus a *fall like behavior* at the high frequency band) at both quiet and perturbed stance conditions as well [35]. Furthermore DETES is also being used for monitoring/following the progress of the disease in both UVL and BVL patients by being tested for their daily life performances at their compensation period after acute dizziness/vertigo attack [36]. On the other hand, the Vestibular Lab where DETES is mounted, is specialized for reporting whether the reason of the complaints of the navy staff about suffering from dizziness is due to the motion sickness, through simulating sea conditions [37].

We are planning to develop an electrophysiological unit to be integrated to DETES for recording electro-potentials from the muscular contractions precisely synchronized with mechanical perturbations during perturbed trials for understanding/investigating the postural control strategies. It is also important to use electro-potential recording unit for delivering an active impulsive stimulus intervening to either sensory (Group Ia, see, Figure **3**) or motor neuronal (α motor neuron) activation in order to understand the role of proprioception (by modifying stretch reflex response [14, 15]) in postural control strategies/mechanisms.

CONCLUSION

The human balance system having redundancies at sensory systems delivering information to hierarchically structured processors acting at sensory fusion in different domains (such as time, frequency, etc) and/or at motor actuators (either having many muscles acting on a joint or an actuator spanning more than one joint, polyarticularity) presents a complex dynamics, where nonlinear dynamical tools of investigation becomes inevitable, especially to understand *how the information arises*. The developed test system (with its ambience) considers and is aware of the importance of ecological roots in deciphering postural control strategies (especially related to vestibular components), thus is cautious in designing either quiet or perturbed stance trials and analyzing the relevant data.

ACKNOWLEDGEMENTS

Subjects gave written consent for the data used at the Case Study. DETES was supported by Scientific and Technological Research Council of Turkey (R&D Financial Support Program for Small-medium sized Industrial Co-operations), Grant No. 7110567 (Hidropol Engineering Co.) and Ankara Development Agency (Financial Support Program for Innovative Technologies), Grant NO. TR51/11/YEN (Hidropol Engineering Co.).

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Received on 21-09-2016 Accepted on 17-10-2016 Published on 03-11-2016

http://dx.doi.org/10.15379/2409-3394.2016.03.02.02