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Model identification and evaluation of postural dynamics of healthy and post-stroke individuals under unidirectional perturbations

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ABSTRACT

In this paper, different techniques of analysis have been used to study the effects of perturbations generated from a robotic mobile platform called Isiskate. These disturbances were applied on two categories of people: post-CVA subjects suffering from cerebrovascular accident and healthy individuals. Our aim is to analyze some assessment tools to distinguish between different postural behaviors. In relevant works, very few studies have addressed the use of nonlinear time-series methods in diagnosis of post-CVA pathological postural behavior. Furthermore, our tools are based on parametric and non-parametric identification procedures, that can yield to an insight on how to improve the examination time. As part of our analysis, the tests were established with several levels of sinusoidal vibrations, along the anterior–posterior (A/P) and medial–lateral (M/L) planes. The mobile platform allowed us to record a set of coordinates that includes center of pressure (COP) as a function of time. First, we have quantified some linear parameters and spectral characteristics using power spectral density (PSD). Thereafter, we have deduced stochastic parameters using stabilogram diffusion analysis (SDA), which revealed some interesting invariants. Then transfer functions between the platform velocity and COP trajectory were evaluated. They were carried out at frequencies from 0.1 Hz to 3.3 Hz. Furthermore, we accomplished a comparison of models based on both parametric and nonparametric identification methods. The combination of the proposed techniques has provided us an understanding of human control process by establishing a behavior model and helped us to distinguish patients with postural disorders. This improves postural analysis and facilitates the diagnosis of pathologies related to equilibrium which serves in rehabilitation.

1. Introduction

One of the main impacts after a stroke are the deficiencies caused by the damage of certain cerebral tissues [1]. The consequences are degradations in the neuronal connections between the brain and the muscles that affect information loop of the somatosensory system and can lead to motor weakness and difficulties to achieve movements [2]. In fact, stroke patients may suffer from sudden falls following neurological lesions [3]. These sensory deterioration affect the proprioceptive system that identifies and orientates the body segments in space [4] and can induce a dysfunction in inter-limb connections due to a limited sensorimotor activities [5].

In 2008, 105,000 hospitalized stroke patients were carried out in France, 50.3% among them suffered from balance and walking disorders [6]. Different studies have been conducted to assess the circumstances of falls and all alterations in the postural control system related to stroke and aging. According to the world health organization: 37.3 million falls occur each year causing serious injury and disability or death [7]. Several approaches were proposed to improve the locomotor capacities of post-CVA patients. Cardiovascular weakness rehabilitation using treadmill exercise is an appropriate rehabilitation method [8]. The audio-visual biofeedback method is also capable of improving the proprioceptive system for better control of joints movements [9,1]. Several studies show that pilates exercises strengthen balance ability and postural fitness of post-CVA patients [10]. It is noted that clinical tests are the only way to investigate the causes of postural disorders in order to limit their consequences. During these tests, therapists are able to record subjects progression without necessary of including biome-

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chanical data [11]. With a suitable dynamic model and through kinematic measurements, we can calculate the forces and torques applied on joints and segments of human body to give more insight to its interaction with the environment [12]. Our work aims to use a robotic platform equipped with force-plates called Isiskate [13]. This platform makes it possible to mimic disturbances in transit and to measure their effects on posture. In response to perturbations, the postural control system chooses the best control strategy to coordinate the muscles contractions in order to maintain equilibrium [14]. The corrective signals try to keep the COP within its security limits. For all tasks, corrections in body dynamics through the central nervous system can be maintained by three types of postural control strategies: ankle, hip and step strategies [15]. Under low-intensity of sagittal perturbations, the postural control system mainly uses ankle strategy, in which the control system rely on ankle couple. Therefore, a model of an inverted pendulum is appropriate to represent a standing equilibrium [16]. During static or dynamic state of a human subject, the COP signal is intrinsically non-stationary and it is also known as a random motion [17]. Collins and Luca (1993) considered the COP trajectory as a stochastic process that can be modeled as a fractional Brownian motion [18]. Furthermore, they have carried out a statistical analysis to quantify the dynamic characteristics of stabilograms. They highlighted two main mechanisms of the postural control system: an open loop and a closed loop control one. The COP is positively correlated with the movement of the platform during the open-loop control phase and it is negatively correlated during the closed-loop control phase. This random behavior of COP displacement revealed an intra-class correlation between subjects. Our objective is to analyze experimental data associated with post-CVA patients to find correlations and to distinguish their postural control phases.

In literature, different studies were conducted to evaluate the postural behavior of post-CVA patients. Silva et al. have found that post-CVA patients suffer from neuronal lesions in ipsilateral limbs during midstance gait, this criterion can be used to distinguish stroke individuals [19]. Furthermore, they also used muscle activation timing to assess the anticipatory postural adjustments of post-CVA subjects in transition between sitting and standing compared to reference individuals [20]. Several studies compared the postural behavior of post-CVA and healthy controls using COP-related stabilometric parameters using traditional linear techniques [21,22]. The COP metrics are also suitable in evaluation of post-CVA postural behavior before and after rehabilitation and recovery [23,24]. However, in term of quantification methods, very few works have addressed the use of COP-related non-linear variables such as SDA to assess the impaired postural control after stroke and to distinguish their pathological postural behavior. Therefore, employing transfer functions and non-linear methods in diagnosis and discrimination of post-CVA abnormal postural behavior has not been fully investigated. In our article, we proposed a new technique to investigate the upright balance control during unidirectional disturbances and to characterize and distinguish post-CVA patients using statistical inferences. Our proposed techniques are combined of linear traditional methods which are a useful approaches for evaluating postural stability [25]. Moreover, nonlinear SDA approaches have been investigated to evaluate the stochastic nature of COP. Finally, we propose a parametric system identification algorithm that is based on platform velocity and COP measures.

In Section 2, we describe the experimental protocol and the theoretical aspects of our proposed methods. Section 3 is dedicated to characterization and identification of the reference group using spectral analysis and traditional parameters, as well as parametric and nonparametric modeling that yielded to an interesting comparison patterns. Section 4 is dedicated to the comparison between a group of healthy references and post-CVA patients using transfer functions and SDA. The last two sections are devoted to some discussions and conclusions.

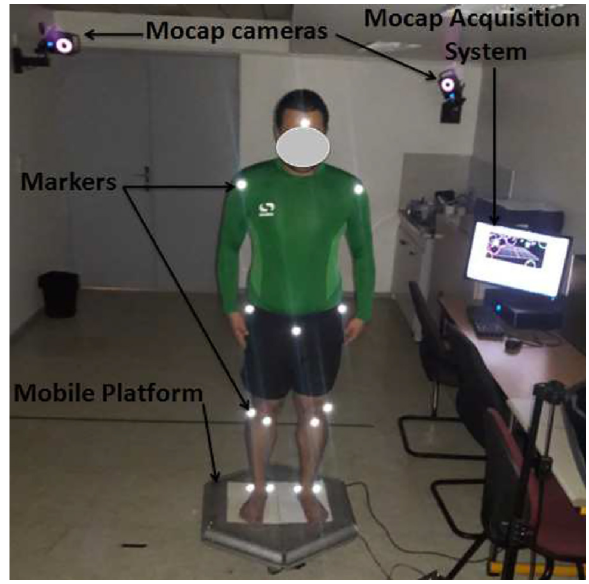

Fig. 1. Data acquisition protocol: a mocap system for real time measuring of body coordinates in space, it is combined of markers, infrared cameras, an acquisition unit and an analyzing computer for data pre-processing. The mobile platform is used to generate movements and to measure COP time series.

2. Materials and methods

2.1. Experimental setup and data acquisition

The experimental protocol was carried out in LISV laboratory (University of Versailles, France). Nineteen volunteers have participated in this study (mixture of males and females). They were divided into two groups: thirteen healthy young adults named reference group, with no neurological or musculoskeletal weakness and none of them has joint or muscle infection (age: 23.61 ± 1.2). They are also free of any kind of balance anomalies. Six post-CVA subjects suffering from stroke syndromes (age: 45.66 ± 19.2). All subjects were in a standing position with eyes open and parallel feet.

Our experiments were carried out on a mobile platform called Isiskate. This platform includes four motorized axles that are adapted to execute translational and rotational movements. Force sensors are attached to the plate to measure the forces exerted by the subject. Subsequently, we measured the COP trajectory with a resolution of 0.05 mm and a platform linear displacement resolution of 0.5 mm [13]. Besides, we used a mocap device to track the position coordinates of the force platform and subject's posture (see Fig. 1). The subjects were exposed to different disturbances at frequencies ranged from 0.1 Hz to 0.5 Hz with data acquisition duration set to 13 s for each test. Practically, this test period allows us to avoid fatigue of subjects with post-CVA syndromes. From the recording of successive COP positions at 100 Hz sampling frequency, the statokinesigrams were plotted with two directions: the sagittal direction (COPx) and the frontal direction (COPy). Fig. 2a and b shows the COP statokinesigrams by separately applying anterior–posterior and medial–lateral perturbations named P(A/P) and P(M/L), respectively. The root mean square (RMS) was calculated to assess the relation between sway activity and the direction of disturbances. It suggests that the sway instability was correlated to the direction of perturbations. Hereinafter, we proceed to the