Balance control adjustment to load impact perturbation – A transfer function model-based analysis

Olivier MARTIN[a,b]*, Emmanuel WITRANT[a,b], Sufiyan N'YO[a,b]

[a] *GIPSA-lab, Grenoble, France;* [b]*Grenoble-Alpes University, Grenoble, France.*

1. Introduction

When upright standing equilibrium is impaired by an external perturbation, balance is maintained using the central integration of sensory signals. Adaptive postural commands are computed on-line, automatically or intentionally, from the sensory inputs regulating the motor outputs. This study focuses on the effects of a push-like perturbation on stance reactive control. Experiments are carried out to provide a real balance dataset, which is used to derive a linear dynamical system (after some transformations) parameterized as an autoregressive model with exogenous input (ARX). Our goal is to propose a data-based model of adaptive balance behaviour using a system identification method. Mixed balance perturbations are considered, as met in everyday life, sports, or therapy, as previously experienced with vestibular patients (Voda et al., 2019). Although identification studies usually challenge static standing posture maintenance with external forces (e.g., Engelhart et al., 2014), our purpose specifically concerns the intentional balance control in response to an anticipated external load perturbation in a predictive-reactive equilibrium control in normal subjects.

2. Methods

The experimental conditions and data acquisition were obtained in 2019 and are briefly described here (see N'Yo, 2019, Master's thesis, for more details).

2.1 Participants

Four males and one female, aged 25 to 56 years old, participated in the experiment and gave their informed consent according to ethical research standards. Two subjects were Tai Chi Chuan (TCC) experts, three had no previous experience.

2.2 Postural task

The participants stand upright on a force plate in a TCC posture with a defence attitude, i.e., an arm-hand segment placed forward at shoulder height to resist the load impact (Fig.1). The postural task implies controlling the whole-body equilibrium despite a load perturbation applied at hand level by a passive inertial pendulum device. It produces an impact load on the hand-arm segment and is discharged after impact using a manually activated quick-release device. The subjects have to control the imbalance while maintaining their posture.

2.2 Protocol

The standardized postural tasks sequence consists of a VISION x LOAD crossed-protocol. The two VISION conditions, Closed-Eyes vs. Open-Eyes, are repeated in the two LOAD conditions: No Load on the pendulum vs. With Load (with an additional 5kg load). The tasks sequence is ordered as follows, with 10 trials per task: 1. Opened Eyes, No load; 2. Opened Eyes, With Load; 3. Closed Eyes, No load; 4. Closed Eyes, With Load. This design generates a trial-dependant level of work and constraint on the balance, once the load is suddenly applied to the subject's hand-arm segment.

2.3 Data acquisition

A MOCAP Qualysis system records both the pendulum (load) trajectory to calculate the force impact value in terms of the input (pendulum work in Joule (J)) and the impact time, as well as the hand-arm and whole-body anatomical landmarks (Fig.1). A Kistler force plate records the ground reaction force (GRF) to compute the resultant force from the 6 DoF components (Force plate (N)) (Fig.1). All data acquisitions are time-synchronized.

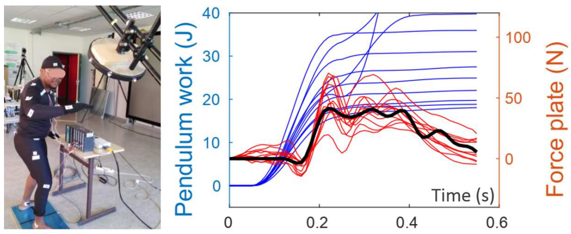

Figure 1. Left: subject standing on the force plate, facing the load perturbation device. Right: Time plot of the input values (pendulum work in Joule (J), blue left scale), the output data (GRF in Newton (N), red right scale), and the simulated response from the transfer function (black large line).

2.4 Data analysis

The relation between the perturbation characteristics and the postural behaviour is characterized by the ARX transfer function model (Fig.1, black thick line). Reasonable fits for each position and for each subject are obtained with ARX models of order 10 and by choosing the optimal fit (minimizing the least squares error) for a time-delay varied between 10 and 200 ms. The model input is the time evolution of the perturbation, characterized by the work of the load applied on the hand-arm segment. The model output corresponds to the GRF time sequence (Fig.1, force plate values). The transfer function is determined for each specific postural task (Load x Vision conditions).

We consider a class of autoregressive models with exogenous inputs (ARX) that writes as:
$y(k) = -a_1 y(k-1) - \ldots - a_{na} y(k-n_a) + b_1 u(k-1) + \ldots + b_{nb} u(k-n_b)$, where y(k) is the square root of the sum of the squared components of the reactive force measured by the force plate, u(k) is the work done by the pendulum force on the wrist, k is the time instant of the data sample, n_a and n_b define the number of past samples (outputs and inputs, respectively) used to compute the model, and $\{a_1, ..., a_{na}, b_1, ..., b_{nb}\}$ are constant parameters that are optimized to minimize the expectancy of the squared modelling error.

3. Results and discussion

3.1 Results

At a behavioural level, the comparative analysis of the pendulum work vs. force plate time-series for all the postural conditions shows both LOAD and VISION main effects (comparison between lines and columns in Fig. 2) and their interaction. The postural reaction is correlated with the intensity of the balance perturbation; the augmentation of the pendulum work applied to the hand-arm segment significantly increases the GRF values. Additionally, time-series comparison shows a significant increase in the GRF in the 'Closed-Eyes' condition, with a cumulative interaction effect in the 'With Load' condition.

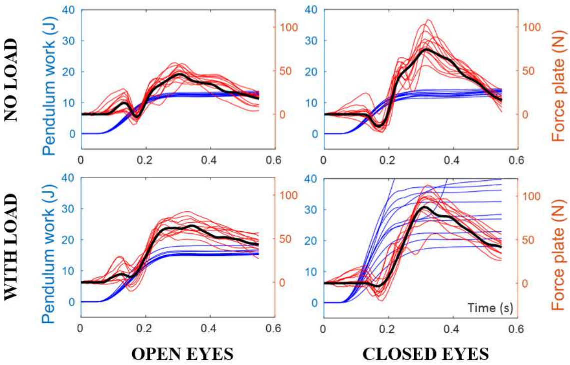

Figure 2. Comparison between the pendulum work (perturbation values as input; blue right scale), the force plate data (GRF as output; left red scale), and the transfer function model (black large line), for LOAD (No/With Load) and VISION (Closed/Open Eyes) conditions. Data for a Tai-Chi expert.

The transfer function (TF) results obtained from the identification procedure show that the model results fit well with the behavioural data (Fig. 2, black large line), as a representative mean estimation of the overall trials effect for each condition of Load and Vision. The TF response captures both the amplitude and transient behaviour of the response (GRF). These results demonstrate that the complexity of the adaptive postural reaction in response to load and vision perturbations can be captured by a simple linear model with a reasonable number of degrees of freedom.

3.2 Discussion

From a neuro-biomechanical point of view, this study shows that during the external perturbation of balance, the compensatory postural adjustments rely (1.) on the related characteristics of both the sensorimotor disturbances (load and vision) and the biomechanical constraints (reaction force) and (2.) on the on-line reactive strategies used to maintain balance control.
In this analytic framework, the TF based on the ARX model is able to characterize and estimate both the perturbation constraints and the effectiveness of the associated postural adjustments. Consequently, the optimized parameters in the TF model allow us to clearly characterize and clarify the impact of sensory and physical constraints on adaptive balance control. Finally, this study demonstrates that context-related balance control can be appropriately modelled by input-output identification.

4. Conclusions

The use of TF methods for an in-depth analysis of postural control processes is of real interest, as is questioning the processes of balance impairment restoration or optimization. Exploring the identification parameters could give us additional knowledge for further assumptions about the adaptive stimulus-response trade-off in balance control.

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***Corresponding author. E-mail:**
olivier.martin@gipsa-lab.grenoble-inp.fr