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Visual-vestibular compensation in balance recovery: A transfer function model-based analysis

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Abstract – During immersive balance rehabilitation, automatic visual-vestibular compensations occurs to reduce the patients' visual reliance and improve the equilibrium. This paper describes the use of an identification procedure to characterise the relationship between visual stimulation features involved in this adaptive sensory compensation, and the balance improvement. The purpose is to determine the stimulus-response transfer functions (TF) associated to the equilibrium enhancement. Standing vestibular patients were stimulated by visual virtual flows, whose pattern and speed changed throughout successive stimulation sessions. The analysis of the feet centre-of-pressure, disequilibrium, and identified models parameters for one representative vestibular patient, showed that TF parameters evolved related to the gradual balance recovery boosted by the visual-vestibular compensation. This results suggest that identified TF parameters are suitable indicators for measuring the effect of sensory substitution on equilibrium recovery. This first step to model the relationship between the sensory re-weighting flexibility and the adaptation of postural commands is essential for future clinical studies using identification methods for sensorimotor evaluation in individualized vision-based balance rehabilitation.

Keywords: Human balance deficit, visual-vestibular compensation, virtual reality, rehabilitation, sensory integration, transfer function model, adaptive motor control, modelling.

1. INTRODUCTION

In control system theory and computational neurosciences, many control models, from sensory feedback integration to motion planning, question the movement and balance control and adaptation by describing the sensorimotor interactions leading to motor co-ordination (Engelhart *et al.*, 2015; Venture *et al.*, 2009; Rougier, 2007; Kuo, 2005; Karniel & Inbar, 2000; Johansson *et al.*, 1988). Although these models clarify how a broad multisensory integration optimizes a global motor control in a healthy person, none of them describes how specific sensory compensation can reduce motor deficits. It is the case for vestibular patients for whom an automatic visual-vestibular substitution emerges during balance rehabilitation, which adapts sensorimotor control to maintain a relative efficiency of the equilibrium commands. Therefore, the identification of indicators of this compensatory sensorimotor transformation appears to be a fruitful approach to assess the evolution of balance recovery.

1.1 Visual-vestibular compensation in balance restoration

In Human, uncompensated balance troubles due to peripheral sensory disorder result from an integration deficit of the vestibular inputs in the processing of balance motor commands (see MacKinnon, 2018 for a review). Even if the upright standing stability is under the control of multisensory interactions, the degradation of the vestibular sensory input, from inner ear damage, reduce the efficiency of the dynamic control of the whole-body equilibrium. In such cases, an

automatic process of sensory re-weighting compensate for the deficiency of vestibular inputs by increasing the relative weight of visual ones during the multisensory processing in order to preserve the upright standing. Consequently, the visual inputs are progressively substituted to the unreliable vestibular ones to preserve the balance control. Although this adaptive sensory compensation strategy helps patients to maintain an efficient balance control in static visual environment, with time the overuse of the visual cues induces gradually a strong visual-dependency that leads the person to an incapability to preserve balance control during upright standing when the visual surround moves. The therapeutic approach to stop this detrimental visual-vestibular substitution that degrades equilibrium is to reduce the impact of the visual inputs by using optokinetic stimulation based on visual flows stimulus (e.g., Pavlou, 2010). This creates illusion of whole-body movement, and consequently postural instability, even falls. In reaction to this visually-triggered balance perturbation, the sensory system decreases the use of the visual inputs become unreliable, because of this, but re-integrates the residual vestibular signals in addition to proprioceptive ones in the balance control processes. Although the visual-vestibular compensation for postural enhancement is classically used in balance rehabilitation therapy (Lacour & Bernard-Demanze, 2015) and its neural substrates partly identified (Dieterich *et al.*, 2007; MacKinnon, 2018), little is suggested about the dynamic control model that could corroborate the processing of adaptive postural commands from sensorimotor transformations based on visual compensation.

1.2 Rationale between balance rehabilitation and sensorimotor transfer function model

Despite the existence of neuro-computational closed-loop models showing shared processes between vestibular, visual and somatosensory signals (input) and subsequent motor commands (output), no study has yet investigated if transfer functions (TF) models can be used to estimate the evolution of the sensorimotor parameters during balance restoration. The lack of knowledge and specific analysis on this converging questioning between system control theory and the sensory control of postural motor commands, makes us consider the preliminary results presented in this paper as pertinent data on the TF-based analysis model applied to adaptive sensorimotor control in rehabilitative balance re-learning.

1.3 Goals of the study

The goal of the study is to take advantage of control theory to characterize the effect of the dynamic visual stimulation on the reactive-to-adaptive transformation of balance motor control, specifically for chronic vestibular patients. The raised question at a neurobehavioral level is to know if the TF-based analysis of the balance re-learning can characterize the equilibrium restoration dynamics, from the sensory re-weighting due to the visual-vestibular compensation triggered by visual stimulation, to the improvement of balance control due to the adaptation of the postural commands. Then, our approach points the relevance of using the formalism of TF models to (1) characterize the motor control system from the adaptive balance commands as outputs, related to visual signal as inputs; and consequently, (2) estimate the therapeutic suitability of the TF-based analysis for the study of the balance recovery processes, and more specifically for the patient-centred rehabilitation protocol. We hypothesised that the parameters estimation of the identified TF could corroborate the adaptive sensory compensation observed in balance

restoration. The evolution of the TF parameters could give pertinent data on the dynamic relation between the sensory flexibility and the postural process, and thus, practicable information for vision-based balance rehabilitation.

2. METHOD

The device and protocol developed for this clinical study consisted in immersing vestibular patients in a virtual visual environment producing moving visual scenes, whose shape and speed characteristics changed during the immersion periods. The visual flows provoked balance perturbations that triggered automatic and controlled postural reactions in patient, to preserve the upright standing. The characteristics of visual stimulation and the correlated balance control data are considered respectively as the input and the output signals for the identification model (see details below). Although an overview of the whole experimental protocol is presented below, only a part of the experimental conditions are used for the analysis of this preliminary data set.

2.1 Participants

In the whole clinical study, nine vestibular patients (5 females, 4 males; 42-64 years old) with chronic unilateral vestibular areflexia causing visual-induced dizziness and recurrent balance disorders, participated in the experiment. All patients gave their informed consent to be included in the study associated to their medical follow-up. The experiment has been approved by the Ethics Committee for Health and Clinical Research of the Grenoble-Alpes University Hospital, in accordance with the Declaration of Helsinki. In this paper, we present only preliminary results for one representative vestibular patient (a 61 years old man).

2.2 Experimental setup

The patient immersed in a virtual reality room, stood in front of a large screen on which video sequences of bubble-like moving visual stimuli (VS) were back-projected (Fig.1). These widescreen visual flows filled the patient's visual field in order to suppress any static visual cues. Patient was instructed to maintain an upright posture as stabilised as possible despite the balance perturbations triggered by the visual flows. To prevent the fall risk but leave the patient free of their whole-body movement to react as comfortably as possible, no harness was used but two supporting tables were positioned beside the patient and a medical assistant stood behind him.

2.3 Protocol

The clinical protocol lasted 8 weeks and consisted in height VS sessions (S1 to S8), once per week. For the 4 first sessions (S1 to S4), a static visual fixation point was displayed in central location on the screen, enabling a visual anchor to stabilize the patient balance during the visual flows. A part of the S1 was devoted to protocol explanations and security instructions. For the 4 last sessions (S5 to S8), the visual fixation point was removed. In this article, are only presented results for session 1 and session 3, during which most of the patients showed a higher reactivity to visual flows with significant signs of balance restoration.

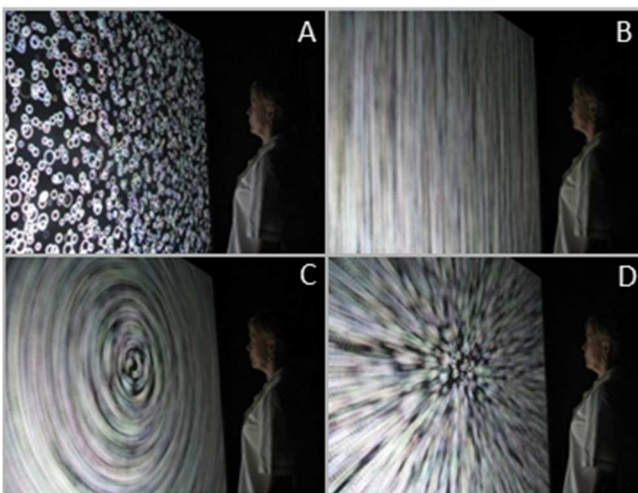


Fig. 1. The immersive virtual-visual room – Experimental setup for patients balance analysis (standing on a force – plate) in condition of visual stimulations (back-projection of optic flows): A. Rest; B. Scroll (Up, Down); C. Rotation (clock, counter-clock); D. Expansion (forward, backward).

2.4 Visual stimulation

The visual stimuli consisted in optic flows, back-projected on a large screen, based on the standardized optokinetic stimulation scenario, and optimized for vestibular patients (Fig.1). For a full session, five visual flow stimulation were used (scroll Up, scroll Down, Clockwise rotation, Counter-Clockwise rotation, Expansion). Six flow speed (FS) conditions were progressive applied to the visual flows, ranged from FS1 to FS6 (from 30 to 240 p.d.u. velocity; procedure defined unit). In this article, are only analysed the 'Up' visual flow condition, for the two flow speed FS1 and FS6.

2.5 Trial sequence

For each session, the sequence of VS was composed of a first rest period of 5 sec., followed by the visual stimulation period of 15 sec., ended by a rest period of 5 sec. Thus, two successive VS were separated by a rest period of 10 sec. The standardized pseudo-randomized sequence displayed successively 8 trials from the different VS, for a total duration of 3 min. 20 sec. This standardized trial sequence was repeated successively for each of the 6 FS, with long rest periods in-between (5 min). The total duration of the immersion was about 20 minutes.

2.6 Balance data acquisition and analysis

To measure the patient balance responses to VS, a Wii Fit™ board was used as a balance plate form to record the centre of pressure (CoP) at feet level, at a 100Hz sample frequency. The CoP corresponds to the ground reaction force applied by the patient to counteract the displacements of the whole-body centre of mass during postural sways. The CoP data is representative of the upright standing stability. Its position was calculated from the x and z coordinates of the plate form corners sensors, and filtered with a 10Hz low pass filter. The CoP trajectory length, and the disequilibrium indicator (DI), detected when the weight loss exceeded 5% of the patient weight indicating a step-off (n ratio), were analysed as dependent variables affected by the visual stimulation conditions.

2.7 Statistical analysis

As mentioned, in this paper are only presented here the preliminary results for one representative vestibular patient, for the two sessions S1 and S3, the two flows speed FS1 and FS6, for the 'Up' visual stimulation. The full data set will be used later for further analyses. Thus, the statistical factorial design corresponds to [2 Sessions (S1, S3) x 2 Flow Speed (FS1, FS6)] in order to focus on the main factors that affect the CoP trajectory and disequilibrium of the patient.

2.8 Transfer function model for human balance assessment

Given that the general neurobehavioral model of human balance control considers that the stabilizing motor commands depend on the characteristics of sensory signals, a transfer function (TF) model is applied to analyse the relation between the input function related to the visual stimulation characteristics, and the output function related to the balance control data (fig. 2). In this approach, a linear behaviour is considered. In general, the model can be non-linear, but in this preliminary study linear model is identified, due to its clear interpretation in terms of dynamical characteristics.

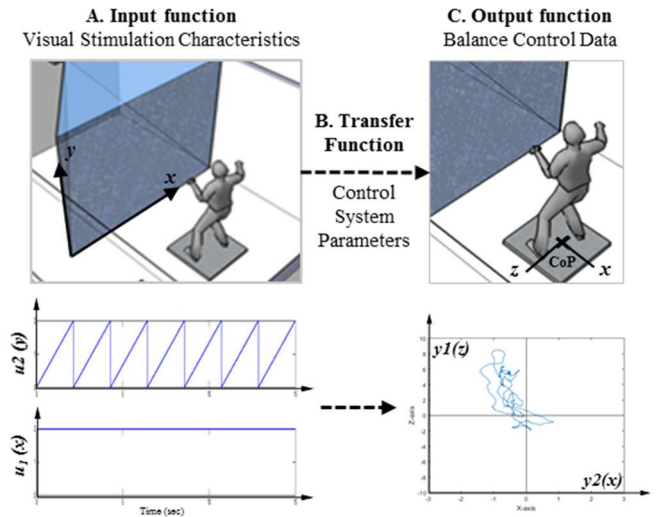


Fig. 2. Relational model between the input function (A. Visual stimulation with x - y decomposition for the Up condition), the transfer function (B. Control system parameters) and the output function (C. Balance control data measurement with x - z co-ordinates of the CoP trajectory).

Input characterisation. The visual stimulations are characterized by the x and y co-ordinates of the visual flow, corresponding respectively to the lateral and vertical displacement of the flow. There are considered as the sensory inputs in the TF model. In Up condition, the visual flow moved only in a bottom-up direction, without any lateral displacement of the flow (fig.1.B. and fig.2.A.).

Output characterisation. The patient's balance reactions are characterized by the x and z co-ordinates of the CoP applied to the force plate. There are considered as the motor outputs in the TF model (fig.2.C.).

Transfer function. The sensorimotor transformation system for balance control is described as the transfer function between input and output function (fig.2.B.). The estimation of model parameters is obtained using identification procedures and performed for each trial. Let us remind that the analysis of the TF parameters changes to assess balance control improvement is the central goal of this study.

3. IDENTIFICATION

The TF model G which represents the transfer from the input to the output as $y(t) = G u(t)$ is determined through an identification procedure, using input $u(t)$ and output $y(t)$ signals. As the input-output relations written here in time domain, G represents the transfer operator. In frequency domain, G represents the transfer function. For sake of simplicity, G will be further referred to as transfer function for both domains (time or frequency). In this study, the input $u(t)$ is a 2 dimension signal with u_1 the horizontal component of the visual stimulus and u_2 the vertical one (mentioned respectively as x and y co-ordinates on the projection screen). The output $y(t)$ is also a 2 dimensional signal, with y_1 the lateral displacement of the CoP (mentioned previously as z co-

ordinate on the force plate) and y_2 the anterior-posterior displacement (mentioned previously as x co-ordinate on the force plate). The model G is a 2 input 2 output one, characterized by 4 transfer functions $G_{11}, G_{12}, G_{21}, G_{22}$, as follows (1):

$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{pmatrix} \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} \quad (1)$$

The identification procedure used an ARX structure of the model and ‘disturbance’ based on system identification principles (Ljung, 1999). It has been conducted using Matlab® software (System Identification Toolbox™). Different orders for the transfer functions have been tried until a reasonable fit is obtained between the measured output and the model output. These results are presented in section 4.2. The choice of the ARX structure is motivated by its simplicity. Other structures like ARMAX or OE have been identified but without major improvement compared to ARX one.

4. RESULTS

4.1 Analysis of the patient balance control

As mentioned above, results analyses focus on sessions 1 and 3, and flow speed 1 and 6. The balance data analysis showed a significant but opposite effect of the *Flow Speed* and *Sessions* conditions on the patient stability. On one hand, the successive augmentation of the visual flow speed during each session (from flow speed 1 to 6), amplifies the balance instability that consequently increases significantly both the CoP trajectory length (160cm with FS1; 325cm with FS6; $p < 0.001$) and the disequilibrium indices (ratio=0.1 for FS1; ratio=1.1 for FS6; $p < 0.0001$) (Fig.3.A.B.). On the other hand, from session 1 to 3, the CoP length trajectory decreases (300cm in session 1; 210cm in session 3; $p < 0.001$) (Fig.4.A.), and the disequilibrium indices decreases from sessions 1 to 3 (ratio=0.5 in session 1; ratio=0.2 in session 3; $p < 0.0001$) (Fig.3.C.D.).

4.2 Transfer function fit analysis

The 2 input 2 output model (1) is based on the following relations (2):

$$y_1 = G_{11} u_1 + G_{12} u_2 ; y_2 = G_{21} u_1 + G_{22} u_2 \quad (2)$$

For each model output y_1 and y_2 , the Fit function is presented in the table 1. For identification purposes, the *Up* visual stimulus has been represented as an horizontal noise (the dots appearing and disappearing in a random way) and a vertical step (if a constant speed of the scroll is considered) or in a saw tooth (if the position of a dot in the scroll is considered as scrolling several times during the 15 seconds of the stimulation period). From the Fit values, it can be seen that the TF

Input signal			Session 1				Session 3			
			Speed 1		Speed 6		Speed 1		Speed 6	
Stimulus	$u_1(x)$	$u_2(y)$	$Y_1(x)$	$Y_2(z)$	$Y_1(x)$	$Y_2(z)$	$Y_1(x)$	$Y_2(z)$	$Y_1(x)$	$Y_2(z)$
Up	noise	noise	35.2	68.4	28.9	59.2	54.0	71.1	29.6	50.6
Up	noise	step	42.8	40.1	42.8	57.5	59.1	68.7	49.1	58.2
Up	noise	sawtooth	73.2	77.9	40.0	62.5	58.2	76.2	53.3	55.9

Table 1. Fit values (in percentage) for the identified models of session 1 and 3, for flow speed 1 and 6.

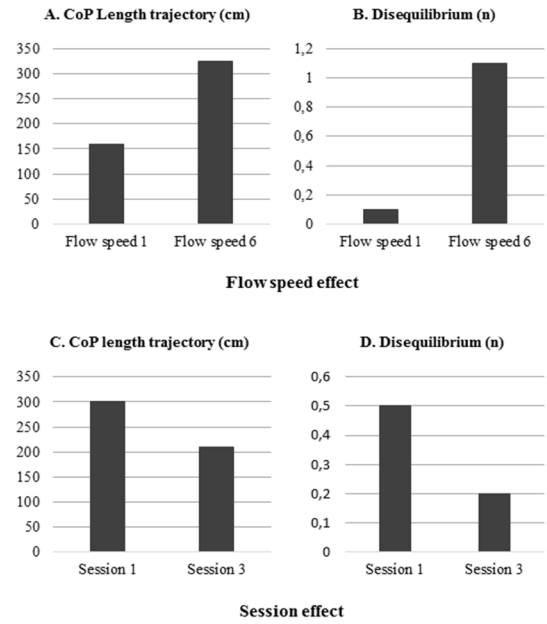


Fig. 3. Evolution of the balance data for a representative vestibular patient: CoP length trajectory (cm) and disequilibrium indices (n ratio). A. and B. Flow speed effect (flow speed 1 Vs. flow speed 6, sessions grouped), C. and D. Session effect (sessions 1 Vs. session 3, flow speed grouped).

representation of the balance behaviour is quite useful. The fit improvement for these cases from session 1 to session 3 could indicate some improvement in balance restoration. In fig. 4 and fig. 5, the model output and the real one are compared for the case *Up* stimulus, the fit values appear also in table 1.

4.3 Transfer function frequency analysis

The frequency analysis of the identified models has been performed, as illustrated in figures 6 and 7, by Bode diagrams showing for the Flow Speed 1 that characteristics evolve from session 1 to session 3. Values are gathered in table 2, where steady state gain, bandwidth frequency, resonance frequency and damping factor are given.

4.4 Relationship between balance data and TF characteristics

Without having considered statistically any causal relationship between balance data and models parameters, a functional relation can however be supposed from the noticeable similarity of their own variations. Indeed, the comparable evolution between the TF characteristics and the balance data, tending respectively towards an optimization criteria and an improvement process throughout the sessions, reflects a substantial relationship between identification parameters and balance efficiency. From session 1 to session 3, for the 4 transfer functions $G_{11}, G_{12}, G_{21}, G_{22}$ the gain values decreases, the bandwidth and resonance frequencies increase, and the damping factor decreases. Given that the increase of the bandwidth indicates a faster response in time domain, associated to the damping decrease it can be considered that throughout the three sessions patient has developed an adaptive balance behavior. The gain reduction shows that the patient became more stable, and the increasing of the

bandwidth indicates that the sensorimotor sensibility increase, given faster postural commands that improves the balance control.

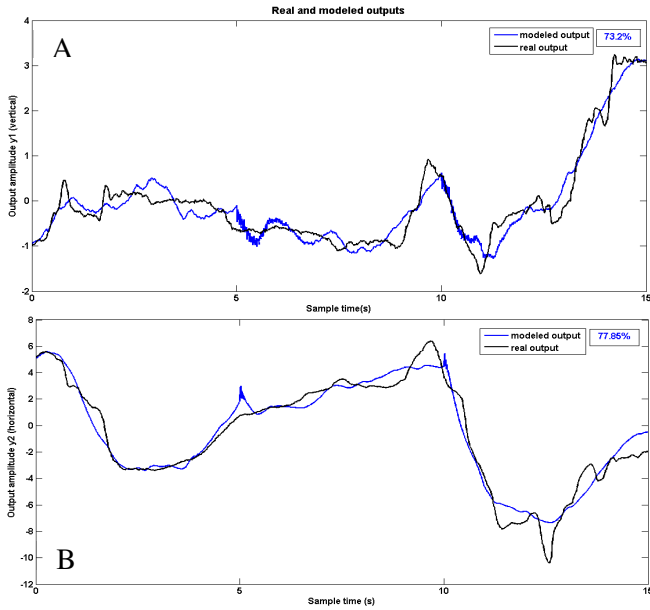


Fig. 4. A. Fit for y_1, U_p stimulus, session 1, flow speed 1, u_2 saw tooth. B. Fit for y_2, U_p stimulus, session 1, flow speed 1, u_2 saw tooth.

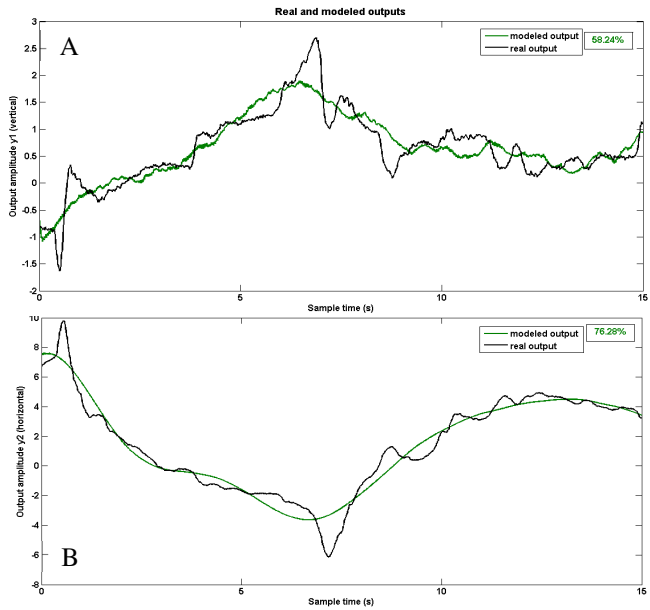


Fig. 5. A. Fit for y_1, U_p stimulus, session 3, flow speed 1, u_2 saw tooth. B. Fit for y_2, U_p stimulus, session 3, flow speed 1, u_2 saw tooth.

	Gain (dB)		Fbw (rad/s)		Fr (rad/s)		Damping ζ	
	Session 1	Session 3	Session 1	Session 3	Session 1	Session 3	Session 1	Session 3
G11	35,79	17,09	0,81	1,79	0,84	1,39	0,77	0,50
G12	50,99	25,05	0,21	0,80	0,22	0,51	1,00	0,14
G21	16,28	-21,96	0,79	0,81	0,51	0,61	0,28	0,07
G22	19,32	-28,05	1,29	2,17	0,46	1,37	0,35	0,16

Table 2. Values of steady state gain, bandwidth and resonance frequencies (Fbw, Fr), and damping factor for the identified models of session 1 and session 3 for the Flow Speed 1.

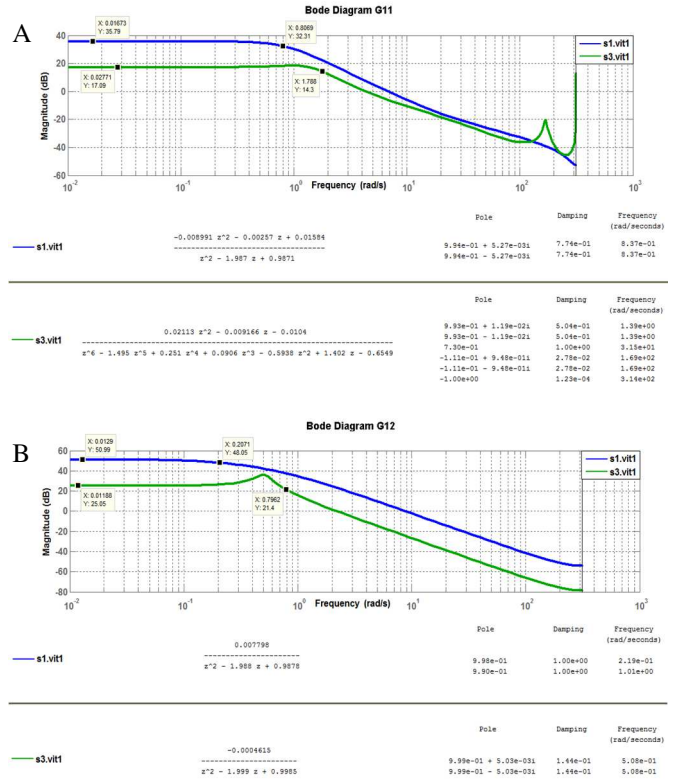


Fig. 6. Bode diagram. Comparison between session 1 and session 3, for flow speed 1, for G_{11} magnitude (A) and for G_{12} magnitude (B).

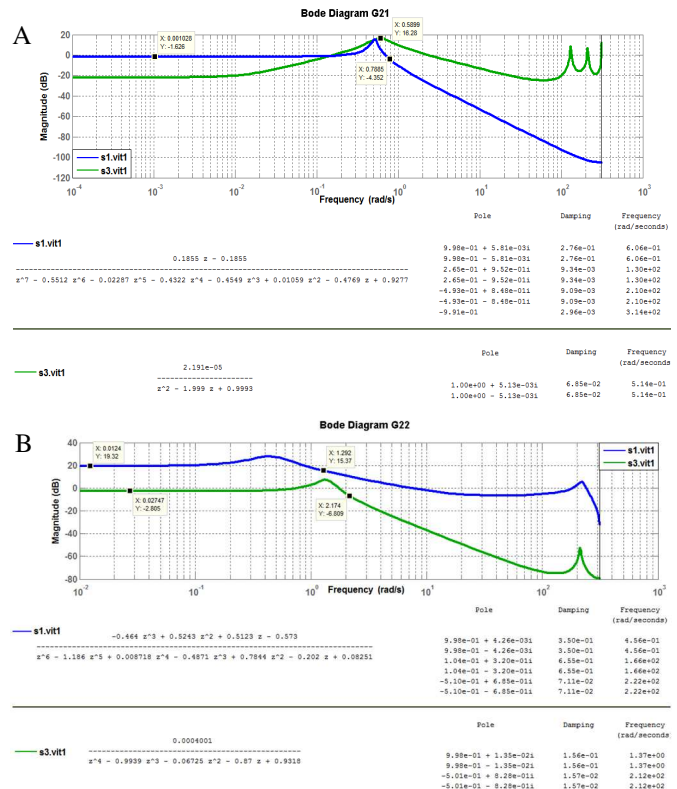


Fig. 7. Bode diagrams. Comparison between session 1 and session 3, for flow speed 1, for G_{21} magnitude (A) and for G_{22} magnitude (B).

5. DISCUSSION

The goal of the present study was to use a control theory approach to describe the effect of the dynamic visual stimulation on the reactive balance commands in vestibular patients. The suitability of TF model has been evaluated to characterize the balance re-learning when a visual-vestibular compensation occurs during a rehabilitation protocol based on virtual optokinetic stimulation. The results analysis for the representative vestibular patient showed both an efficient effect of rehabilitation sessions on the balance data, and an associated evolution of the TF parameters.

5.1 Balance restoration

The analysis of the balance data clearly showed that an adaptive equilibrium process occurred throughout the rehabilitation sessions, despite the increasing task difficulty caused by the visual flow speed. The improvement of patient's stability can be assigned to the decrease of the disruptive effect of the visual flows due to the compensatory re-integration of persistent vestibular signals in addition to proprioceptive ones, into the sensorimotor processing of the balance control. Throughout the sessions, this neural re-weighting strategy reversed progressively the sensory priority; it decreased the visual dependency by minimizing the unreliable visual flows. This generated a sensory re-enrichment for the on-line control processes of the postural motor command which produced efficient stabilizing forces at CoP level. It reduced the patient's disequilibrium and consolidated gradually his upright standing thanks to the emergence of adaptive balance commands.

5.2 Can TFs give estimation of balance restoration?

The frequency analysis of the identified models shows that models parameters evolve throughout the sessions. The model steady state gains become weaker, showing that the patient is less influenced by the visual stimulus and controlled more efficiently the CoP displacement, and thus his posture. The bandwidth become larger, showing that the patient is able to treat (to control) higher visual frequencies. The resonance frequency is also higher, the damping factor is lower, meaning that the patient is 'resonating' to higher frequencies than in the beginning of the experiments. Therefore, as mentioned initially, in terms of sensorimotor control model practicable for rehabilitation, the sensory compensation process observed in patient after three weeks of virtual immersion appears to be the result of the positive input-output effect that links the virtual flows characteristics to the adaptive balance command. We can conclude that the balance re-learning processes objectivized by postural data is corroborated by the TF characteristics. The evolution of the identified parameters is representative of the sensorimotor flexibility developed during the reverse-processing of the visual-vestibular substitution that led patient to reacquire balance control. Consequently, TF could potentially estimate the functional efficiency of sensorimotor controls, and could give valuable prognostic and diagnostic indicators.

6. CONCLUSION

In accordance with our starting hypothesis, this clinical study demonstrates that the TF-based balance recovery analysis can be used to estimate the sensorimotor adaptation, via the

analysis of the changes in both the TFs parameters and the balance data. The balance restorative processes emerging from the sensory flexibility can be describe by system identification models, and the parameters identification appears to be a relevant method for the analysis of the balance adaptation. This approach presents a practicable interest for an individualized rehabilitation for vestibular patients. Further analysis of the complete data set including multidirectional stimulation at different flow speed will evaluate the relevance of the TF models for more complex input-output relationship, in order to assess the real reliability of the identification models for patient's evaluation during vision-based rehabilitation.

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