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Published in:
Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Conference

DOI:
10.1109/IEMBS.2004.1403113

2004

Proceedings of the 26th Annual International Conference of the IEEE EMBS
San Francisco, CA, USA • September 1-5, 2004

Adaptation of Multi-joint Movements during Postural Disturbances

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Abstract—**The objective was to investigate the adaptation of the multi-segmented body movements induced over time by vibratory proprioceptive stimulation of the calf muscles and by galvanic vestibular stimulation. Twelve normal subjects were with eyes open or eyes closed exposed to vibratory stimulation of two different amplitudes and frequencies, or to simultaneously applied galvanic and vibratory stimulation. Multi-input multi-output system identification methods as well as quantitative analysis were applied to the biomechanical experimental data of anteroposterior and lateral body movements and torques induced towards the ground.**

The immediate adaptive response to the stimulation onset was that the subjects adopted a more rigid posture with coordinated movements of primarily head-shoulder and head-hip body segments. The body-movement amplitudes at all measured sites as well as the amplitudes of the ground support forces decreased over time as a result of another, somewhat slower adaptation process. The subjects required more time to adapt to a rigid movement pattern when the subjects were simultaneously exposed to both galvanic and vibratory stimulation. Moreover, the accuracy of the MIMO model and correlation analysis between measured torque variance and head; shoulder; hip and knee movement variance suggests that force platform recordings reflect both in anteroposterior and lateral direction the body movements at these sites.

Keywords—Adaptation; Balance; Posturography; Movement pattern

I. INTRODUCTION

Coordinated control of the body segments is a complex aspect of human postural control, owing to the multiple degrees of freedom of the controlled system. Several interacting subsystems are involved in the dynamics of human posture and locomotion, including the skeletal, neuromuscular and sensory systems. Studies of posture dynamics and stability therefore involve the study of mechanical aspects of the human body, its sensory systems, and the principles governing coordination in motor control [1]. Thus, the postural movements are restricted by the muscular and skeletal organization and by the geometrical configuration of the body consisting of segments moving in an interrelated fashion to each other. The ability to generate motions of the body segments are also restricted by the requirements of muscle force and by the movement flexibility in the muscles, joints and tendons [1-3]. The organization and coordination of the mechanical body motions have been extensively studied from the perspectives of biomechanical, neurological and control system analysis [4-8]. However, the dynamical coupling between body segments where action of one segment will affect the motions of other parts of the body are difficult to analyze both theoretically and experimentally. Several researchers have addressed the problem by studying postural stability during various disturbances of upright posture, and grouped the response body motions according to different patterns or "postural strategies" [7-10].

According to standard precepts of classical mechanics, balancing of the body center of mass by means of ground support forces represents a statically unstable configuration reminiscent of an inverted pendulum. Stabilization of the upright equilibrium of an inverted pendulum requires persistent feedback action with a model complexity at least of order two, i.e., velocity and position, in each spatial dimension. Modeling of maintenance of a stable equilibrium in upright stance would thus require at least four states. Assuming that it is possible to fit an over-parameterized model to accurately represent the input-output behavior, it is relevant to ask whether this model includes a model of single-segment inverted pendulum describing the balancing of the body center of mass by means of support surface forces and moments and whether a decomposition is possible of the biomechanical model into one model component describing inverted pendulum dynamics and residual dynamics including inter-segmental motion, adaptation dynamics, etc. Methods for such investigation require attention and some results are provided in this paper.

The possibility that adaptation and muscle fatigue can lead to multi-muscle and multi-joint coordination changes and in particular movement reorganization has received little attention in previous studies. The study of regulation of the orthograde posture constitutes an essential topic of motor control because of the universal importance of the mechanisms involved. They are used not only to maintain the static posture, but also to ensure body stability during various locomotory movements [11]. The manner in which the CNS might use adaptive adjustments to reduce the likelihood of balance loss is of particular relevance to fall prevention [12, 13]. It is well known that the CNS employ both feedforward (predictive) and feedback (reactive) control to compensate for the perturbations during movement. Appropriate feedforward compensations, based on an adaptive internal model of the system [14] and the expected external conditions, can greatly reduce the magnitude of required reactive responses [13].

Controlled artificial postural disturbances for balance control studies can be induced in various ways. Some methods use physical movements by inducing for example translation or inclination of the supporting surface [15]. Other methods aim to isolate the stimulus effect to a single sensory input, i.e., visual stimulation by altering or moving the visual surrounds [8, 15], vestibular stimulation by galvanic transmastoidal currents or proprioceptive stimulation by vibration of muscles or muscle tendons [15]. Galvanic vestibular stimulation changes the firing rate of the vestibular nerve. A bipolar bilateral transmastoidal galvanic stimulation induce a lateral body deviation towards the anode if a subject stands with the head facing forward [15]. Vibration applied to a muscle or a muscle tendon increase the firing of the muscle spindles, thus signaling that the muscle is being stretched. The stimulated muscle responds to this with a reflexive contraction (tonic vibratory reflex). Calf muscle stimulation induces body sway mostly in the anteroposterior direction. Wierzbicka et al have reported that continuous vibratory stimulation over a longer period (30s) might induce postural post-effects in terms of sinusoidal anteroposterior body sway during upright quiet stance. Nonetheless, no such post-effects were observed after any of the posturography trials in this study probably due to that the average vibration pulse duration was only 3.2s long. The aim of this study was to investigate how the anteroposterior and lateral head, shoulder, hip and knee movements were affected by vibratory proprioceptive and galvanic vestibular stimulation and to investigate whether body movements were affected by adaptation over time. A secondary aim was to investigate to what extent recorded force platform measurement corresponded to actual motions of the head, shoulder, hip and knee.

II. Methodology

All *Subjects*

The posturographic tests were performed on 14 healthy subjects (seven men and seven women; mean age 33.8 years). The subjects had no history of vertigo, central nervous system disease, or injury of the lower extremities. At the time of the investigation, no subject was on any form of medication or had consumed alcoholic beverages for at least 24 hours. The experiments were performed in accordance with the Helsinki declaration of 1975 and were approved by the local ethical committee.

Equipment

Vibratory stimulation was applied to the gastrocnemius muscles of both legs. The vibrators, designed as cylinders of 0.06 m length and 0.01 m in diameter, were attached to the middle of the calf muscles and held in place by elastic straps around the legs. Two kinds of vibrators were used during the trials. The low intensity vibrators had vibratory amplitude of 0.4 mm and a vibration frequency of 55 Hz. The high intensity vibrators had vibratory amplitude of 1.0 mm and a vibration frequency of 85 Hz. The galvanic vestibular stimulation was applied as a bipolar and binaural transmastoidal current of 1 mA amplitude with pseudorandomly changing current direction. The galvanic current was delivered by a computer-controlled constant current generator through two electrodes, made of carbon rubber and 3.5 x 4.5 cm in size (Sentry TENS, Sentry medical products, USA). The electrodes were placed on each of the mastoids and fixated by contact gel and headphones. Shear forces and torques actuated by the feet were recorded with six degrees of freedom by a force platform. Force platform data was sampled at 50 Hz. The body movements at five anatomical landmarks were measured by a 3D-Motion Analysis system (Zebris™ CMS-HS Measuring System). The first marker (denoted Head) was attached to the subject's cheek bone (os zygomaticum), the second marker (Shoulder) to the shoulder (tuberculum majus), the third (Hip) to the hip bone (crista iliaca), the fourth (Knee) to the knee (lateral epicondyle of femur), and the fifth marker (Ankle) to the ankle bone (lateral distal fibula head), (Fig. 1).

Procedure

The subjects were instructed to stand erect but not at attention, with arms crossed over the chest and feet at an angle of about 30 degrees open to the front and the heels approximately 3 cm apart. The subjects either focused on a mark on the wall at a distance of about 1.5 m, or had their eyes closed, as instructed. Before the galvanic/vibratory

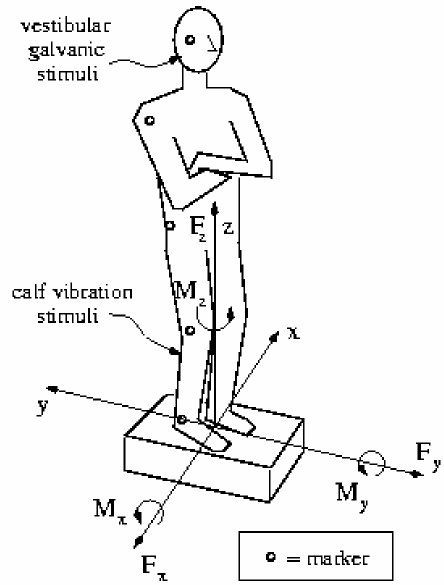

Figure 1. Schematic picture of the five Zebris markers attached on a subject standing on a force platform, the ocations being shown as small circles.

stimulations started, spontaneous sway was recorded for 30 seconds. The stimulations were implemented according to a pseudorandom binary sequence (PRBS) schedule [15]. The galvanic stimulation was applied by turning on the galvanic current and by randomly shifting the current direction, i.e. electrode polarity, according to the PRBS schedule. The vibratory stimulation was applied by turning on or off the vibration according to the schedule. The galvanic/vibratory stimulations were applied with different PRBS schedules to obtain uncorrelated galvanic and vibratory stimulation during the two tests where the subjects simultaneous were exposed to both kinds of stimulation. The subjects were exposed to stimulation for 205s; hence the total test time for all tests including the quiet stance period preceding the stimulation was 235 seconds. Six tests were performed in a randomized order.

1. Eyes closed - low intensity vibration (denoted EC-low).
2. Eyes open - low intensity vibration (EO-low).
3. Eyes closed - high intensity vibration (EC-high).
4. Eyes open - high intensity vibration (EO- high).
5. Eyes closed - Simultaneous low intensity vibration and galvanic stimulation (EC-sim).
6. Eyes open - Simultaneous low intensity vibration and galvanic stimulation (EO- sim).

Statistical analysis

The anteroposterior and lateral body movements were quantified by analyzing the variance of the head, shoulders, hip and knee movements and the variance of the torque induced towards the ground by the body movements. Moreover, the correlation between the individual movements of the head, shoulders, hip and knee were analyzed, as well as angular position of these sites in terms of average leaning angle over time. The angular coordinates was calculated from the difference in height and anteroposterior/lateral position relative the ankle marker. Analysis values were obtained for five periods: the quiet stance period (0–30s) before stimulation was applied, and from four 50-second periods (period 1: 30–80s; period 2: 80–130s; period 3: 130–180s; period 4: 180–230s) during the stimulation. The movement variance values were normalized by the subject's squared height before the statistical analysis thus providing inter-individual compensation for individual movements of inertia. The torque variance values were normalized by the subject's squared height and weight, and for representational purposes multiplied by 1000.

Mathematical Modeling and System Identification

A mathematical description of the stimulus-dependent departures from equilibrium was approached by adopting a state-space model.

$$\begin{aligned} x_{k+1} &= Ax_k + Bu_k + v_k, \quad x_k \in R^n, u_k \in R^m \\ y_k &= Cx_k + e_k, \quad y_k \in R^p \end{aligned} \tag{1}$$

where

- k sample index (time);
- A, B, C coefficient matrices to be estimated by fitting state-space model to data (system identification);
- *{v_k },{ e_k}* stochastic disturbance sequences acting on kinematics and measurements;
- *{u_k}* stimulus sequence;
- *{x_k}* state sequence of linear model (representing velocities, positions and other \`storage´ variables.

Subspace model identification methods

Consider a model described as a discrete-time time-invariant linear system with the state-space equations according to Eq. (1) with zero-mean noise sequences *{v_k },{ e_k}* with covariance matrix

$$\Sigma = E\{\begin{pmatrix} v_k \\ e_k \end{pmatrix}\begin{pmatrix} v_k \\ e_k \end{pmatrix}^T\} = \begin{pmatrix} \Sigma_v & \Sigma_{ve} \\ \Sigma_{ve}^T & \Sigma_e \end{pmatrix} > 0 \tag{2}$$

An innovations model to replace the model of Eq. (1) is

$$\begin{aligned} x_{k+1} &= Ax_k + Bu_k + Kw_k, \quad x_k \in R^n, u_k \in R^m \\ y_k &= Cx_k + w_k, \quad y_k \in R^p \end{aligned}$$

where K is obtained from the positive definite solution P to the Riccati equation.

State-space model identification is provided by the multivariable output-error state-space (MOESP) algorithm [14]:

1. Define the following Hankel matrices of input-output data

$$Y_{rs}^{(k)} = \begin{pmatrix} y_k & y_{k+1} & \cdots & y_{k+s-1} \\ y_{k+1} & y_{k+2} & \cdots & y_{k+s} \\ \vdots & \vdots & \ddots & \vdots \\ y_{k+r-1} & y_{k+r} & \cdots & y_{k+r+s-2} \end{pmatrix}$$

$$U_{rs}^{(k)} = \begin{pmatrix} u_k & u_{k+1} & \cdots & u_{k+s-1} \\ u_{k+1} & u_{k+2} & \cdots & u_{k+s} \\ \vdots & \vdots & \ddots & \vdots \\ u_{k+r-1} & u_{k+r} & \cdots & u_{k+r+s-2} \end{pmatrix} \tag{4}$$

where *r, s* are the numbers of block rows and block columns, respectively, and where k is a time-shift variable,

2. Make the QR factorization

$$\begin{pmatrix} U_{rs}^{(1)} \\ Y_{rs}^{(1)} \end{pmatrix} = \begin{pmatrix} R_{11} & 0 \\ R_{21} & R_{22} \end{pmatrix} \begin{pmatrix} Q_1 \\ Q_2 \end{pmatrix} \tag{5}$$

3. Calculate the column space of the extended observability matrix by means of the SVD

$$R_{22} = \begin{pmatrix} U_n \\ U_n^{\perp} \end{pmatrix} \begin{pmatrix} S_n & 0 \\ 0 & S^{\perp} \end{pmatrix} \begin{pmatrix} V_n^T \\ (V_n^{\perp})^T \end{pmatrix} \tag{6}$$

Then, up to a non-singular similarity transformation matrix U_n provides an estimate of the extended controllability matrix from which estimates of *A, C* may be computed.

4. Use the estimates of and least-squares estimation applied to the state-space model

$$\begin{aligned} x_{k+1} &= \hat{A}x_k + Bu_k + Kw_k, \quad x_k \in R^n, u_k \in R^m \\ y_k &= \hat{C}x_k + w_k, \quad y_k \in R^p \end{aligned}$$

to find estimates of the matrix *B*.

5. Calculate *K* solving the Riccati equation for estimates and obtained from covariance matrix of model misfit;
6. Apply statistical model validation to characterize the model accuracy, prediction accuracy, residual autocorrelation etc..

As for system identification, multi-stimulus multi-response posturography as described Eqs. (1-7) was applied to stimulus-response data [15]. Secondly, multi-input multi-output system identification was applied to the biomechanical subset of experimental data, i.e., ground support forces [F_x F_y F_z M_x M_y M_z] as input signals and position data of body segment as output signals (Fig.1.)

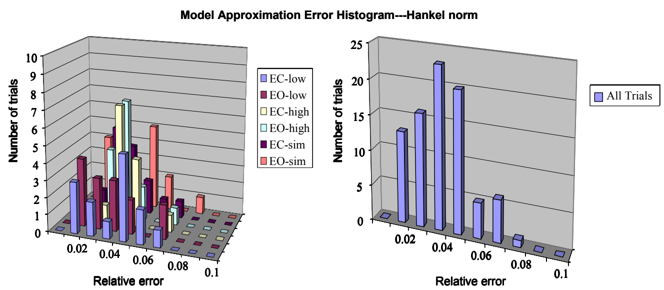

Figure 2. Relative model approximation error measured as Hankel two-norm ratio for individual accurate high-order linear biomechanical models with forces as inputs and positions as outputs when reduced to fourth-order linear models compatible with stabilized inverted pendulum dynamics, the relative error for all test subjects and test condition being less than 0.09 (or 9%).

IV. Discussion

In a series of trials, we have analyzed the induced torques against the surface and the induced movements of the head, shoulders, hip and knee, while in upright stance partly disturbing the receptor information by vibratory proprioceptive and galvanic vestibular stimulation. In line with other reports our findings showed that perturbations evoked both by the vibratory and galvanic stimulations induced simultaneous body movements in all body segments, corresponding to an approximate single-link pendulum pattern.

Inverted Pendulum Dynamics

One of the issues for this study was to verify a correspondence between recorded forces and torques actuated toward the ground by the feet and actual movements of the body. Thus, the true body movement at specific sites is only available from movement analyzing systems such as Zebris™, Selspot™ or Elite™ equipments, which are able to measure the movements of a specific point. We found a large correspondence between the force platform data and actual body motions of the various body sites, especially for the positions close to the center of mass and above, i.e., the hip, shoulder and head. These findings suggest force platform data to correspond to a large extent to actual motion of the body as long as the movements approximately are in accordance with a single-link pendulum pattern.

Stabilization of the upright equilibrium of an inverted pendulum requires persistent feedback action with a model complexity at least of order two, i.e., velocity and position, in each spatial dimension. Thus, modeling of maintenance of a stable equilibrium in upright stance would require at least four states. Our findings suggest that a reduced fourth-order linear model has a capacity to model a wide range of single-segment stabilized inverted pendulum dynamics including anteroposterior and lateral dynamics and various conical pendulum dynamics. Note that the model in the presented case deals with the force-kinematics relationship, i.e., biomechanical input-output dynamics, with no explicit attention to stimulus-response relationship prone to adaptation and other time-varying dynamics. Thus, the models fitted to data of individual subjects under the various tests conditions represent biomechanics only, the stimulus maintaining the excitation condition necessary for identification.

Acknowledgment

This investigation was supported by grants from the Swedish Medical Research Council and the Medical Faculty of the University of Lund.

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