Intermittent delay feedback control as an origin of physiological movement variability

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Summary. In this study, we address issues about human motor control that achieves two apparently contrasting goals at the same time, namely, stability usually with a small variability and flexibility usually with a large variability during movement, on the assumption that neural control mechanisms dealing with this trade-off are the origin of physiological movement variability. In particular, we consider postural control during bipedal quiet standing and so-called human stick balancing task. We analysed experimental data of movement during those motor behaviours in healthy and, for some cases, in patients with Parkinson's disease in order to characterize their movement variability. We mathematically model those behaviours and numerically simulate dynamics of the models, and suggest that the intermittent delay feedback control is a plausible strategy that might be responsible for resolving the trade-off between stability and flexibility, leading to the optimal physiological movement variability.

Introduction

Quantitative characterization of movement variability is of critical importance, because it could potentially provide quantitative measures for clinical diagnosis of motor dysfunction [1]. The concept of optimal movement variability is useful for finding such a good measure if the optimal variability could represent a healthy state of the underlying neuro-mechanical system, and if a certain amount of deviation from the optimality could represent disease dynamics, representing disease severity. Here we address issues about human motor control that achieves two apparently contrasting goals at the same time, namely, stability usually with small variability and flexibility usually with large variability during movement, where each aspect of the movements is indispensable for motor function. We assume that neural control mechanisms dealing with this trade-off are the origin of physiological movement variability. In particular, we consider postural control during human bipedal quiet standing and so-called human stick balancing task. We analyse experimental data of movement during those motor behaviours in healthy and, for some cases, in patients with Parkinson's disease in order to characterize the movement variability in health and disease. We also consider mathematical models of those behaviours and numerically simulate their dynamics. By comparing experimental and simulated movement variability, we suggest that the intermittent delay feedback control is a physiologically plausible strategy that might resolve the trade-off between stability and flexibility, and a loss of intermittency in the control can be a major cause of impaired movement in patients with Parkinson's disease (PD). More specifically, we show that, for each motor paradigm, slow dynamics that are associated with a saddle-type unstable upright equilibrium or a saddle-type unstable periodic gait without active feedback control play a key role for stabilizing the upright posture. Such slow dynamics appear intermittently when the central nervous system suspends the active intervention on mechanical body dynamics, whereby the state point of the mechanical system approach the saddle-point transiently along the stable manifold. At the same time, the intermittent appearances of the slow dynamics might be responsible also for establishing movement flexibility, leading to the optimal movement variability.

Human behavioural experiments and modelling

Postural control during quiet standing

We analyzed postural sway during quiet stance based on the variation in center of pressure (CoP) data that were acquired from healthy young and elderly subjects, and PD patients [2]. Each CoP data was characterized by a number of sway indices including the area of 95% confidence ellipse, the power spectral density function (PSD), the diffusion plot, and the detrended fluctuation analysis (DFA). The human upright posture was modelled by using a single or a double inverted pendulum controlled by delay feedback controllers with small additive motor noise [3,4]. We examined how stability and movement variability of the models change depending on the type of feedback controller, including the standard linear time-continuous proportional-derivative controller and the time-discontinuous intermittent controller.

Human Stick balancing

An experimental system of a single inverted pendulum (stick) on a small cart (cart-inverted pendulum; CIP) was assembled mechanically, and the manual-control performances for stabilizing upright position of the stick were measured from experimental subjects [5]. The CIP comprised a uniform-density thin, rigid stick with a length of 0.5 m and a mass of 0.125 kg, as well as a cart with a mass of 0.25 kg. The cart could slide smoothly along a rail track 0.8 m in length. The cart and the stick were joined by a uniaxial bearing: thus, the joint was considered as a frictionless pin-joint. The stick could rotate only in the two-dimensional plane along the rail track. The subjects manipulated the cart on the track by holding a handle attached to the cart with their right hand. An optical motion capture system with five infrared cameras was used to measure the motion of the stick during the task with a sampling frequency of 300 Hz. Movement variability of the stick and the cart was characterized as in the human quiet standing. Moreover, according to previous studies that report Lévy-like distribution in the velocity-increments during stick balancing, we quantified non-Gaussianity of the cart-acceleration. Dynamics of the experimental system were modeled by a set of equations of motion of the stick and the cart, where the horizontal motion of the cart is controlled by a feedback controller. As in the postural control modeling, we compared performance and movement variability of the model with the standard time-continuous proportional-derivative feedback controller and the time-discontinuous intermittent controller.

Results

Intermittent control as an origin of postural flexibility

We observed that the sway size in most PD patients was significantly smaller than that in healthy subjects. Moreover, comparisons in PSD at low-frequency regime (below 0.7 Hz) explained that the small sway size in the PD patients was due to a loss of the power in the low frequency components [2]. The PSD in the low frequency regime for each of the healthy and the PD patient could be fitted by a straight line with a negative slope. The slope for the healthy subjects was about -1.5, implying existence of the power-law scaling, whereas that for the PD patients was about -0.5, meaning that the low frequency postural fluctuation in the PD patient was more or less close to the white noise [2]. We showed that those characteristics of postural sway in healthy subjects could be reproduced by the inverted pendulum model controlled by the intermittent controller [3,4]. Moreover, a loss of intermittency in the control, by which the controller becomes time-continuous, generates white-noise-like sway patterns in the low frequency regime, suggesting that the strategy transfiguration from the intermittent to the continuous control can be a major cause of postural inflexibility in PD patients.

Intermittent control at the edge of stability as an origin of non-Gaussianity

In a typical movement variability observed in the CIP task from a highly skilled subject, we observed intermittent bursting behaviours in the time series of tilt angle and the corresponding angular acceleration of the stick [5]. Such movement variability could be characterized by the non-Gaussain distribution of the cart acceleration, which exhibits leptokurtosis at the origin and the fat-tail in comparison with a Gaussian distribution. Moreover, the inter-intervention intervals show the power-law distribution [6]. We showed that the non-Gaussian characteristics of the movement variability can be reproduced by the model with the intermittent delay feedback control, in particular at the edge of stability, whereas the continuous control typically generates Gaussian fluctuation only [5].

Discussion

Stabilization of human upright stance during quiet standing requires active neural control, because the passive stiffness of the ankle joint is lower than the growth-rate of the gravitational toppling torque. In the case of stick balancing, there is no passive viscoelasticity at all at the supporting end of the stick, making the balancing more difficult than the postural control. In both cases, active controllers should compensate the risk of delay-induced instability due to the large neural feedback transmission delay of about 0.2 s. The standard linear time-continuous feedback control, such as a proportional-derivative control or the stiffness control is not suitable for avoiding the risk. A robust control strategy that can resolve this vulnerability in the continuous control is the time-discontinuous intermittent control that is characterized by ‘‘on-period’’ and ‘‘off-period’’ of times in activations of the active feedback control force. Among several types of the intermittent control models, we have proposed a control model that exploits the fact that the state point of the upright body and that of the multi-link gait model, respectively, transiently approaches the upright equilibrium and the unstable limit cycle, along a stable manifold of the unstable saddle-type equilibrium that appears in the off-periods during which the active feedback control is turned off [3,4,5]. In those models, the transiently converging saddle-type dynamics during the off-periods are primarily responsible for stabilizing the pendulum, supplemented by the active delay feedback control during the on-periods. Smart switching between those two unstable dynamics can establish robust stability with moderate amount of movement variability. Although the intermittent control model could explain most of the experimental behaviours, it is worthwhile to note that a model with delay feedback supplemented by a model predictive control tuned at stability edge in the feedback gain parameter space could also show a good performance in terms of reprodusability of experimental behaviours during stick balancing [7].

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